HWS/U 2008

Geology of New Zealand Field Trip Guidebook

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Hobart & William Smith Colleges and Union College

2008 New Zealand Guidebook

Nan Crystal Arens and David C. Kendrick

Please read this guidebook before you arrive in New Zealand
Tell your parents that they can get a PDF copy of the guidebook on the web site.
Bring the guidebook with you on the trip.

NOTE: There is a NZ$25 fee to exit New Zealand. You will pay this after obtaining your boarding pass as you prepare to leave the country. Please budget accordingly.

Itinerary

13 Nov. Arrive in New Zealand, store bags and transit to Christchurch
14 Nov. Meet group 9 a.m. for drive to Aoraki
15 Nov. Mueller and Hooker Glacier Moraines—Field Exercise
16 Nov. Travel through Haast Pass to Haast Beach
17 Nov. Alpine Fault and travel to Franz Josef
18 Nov. Franz Joseph Glacier
19 Nov. Travel to Arthur's Pass
20 Nov. Travel to Christchurch (free evening)
21 Nov. 6:45 a.m. flight to Wellington and travel to National Park
22 Nov. Tongariro Crossing or Ruapehu or field exercise
23 Nov. Tongariro Crossing or Ruapehu or field exercise
24 Nov. Tongariro Crossing or Ruapehu or field exercise
25 Nov. Travel to Rotorua and Waimangu geothermal field
26 Nov. Wai-o-tapu geothermal field
27 Nov. White Island and Maori Thanksgiving Feast
28 Nov. Final exam and call home (it's Thanksgiving in the States)
29 Nov. Program ends. Transit to Auckland for departing flights.

Contact Information

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Mobile phone information for Profs. Arens and Kendrick will be posted on the program web site (http://academic.hws.edu/Kendrick/OZ2008) as soon as it is available. This site should also be consulted for any changes in itinerary and important notices.

Because we are almost constantly on the move during the New Zealand field trip, it may be difficult for family and friends to contact you. Furthermore, we will be in some relatively remote areas where internet access may not be available or only available through a very slow dial-up connection that may be incompatible with the HWS and Union mail servers. Where internet access is available, it will likely be on a pay-for-time basis (~NZ$5 for 10-15 minutes). You should plan ahead to call home. Phone cards with reasonable international rates can be purchased throughout New Zealand. In an emergency, family and friends should try first to contact Profs. Kendrick or Arens using the mobile numbers provided on the web site (http://academic.hws.edu/Kendrick/OZ2008). Please note, however, that mobile coverage is not available in all areas we will visit. Failing to reach the program directors, emergency messages can be relayed through the Center for Global Education. We have also provided contact information for each of the places we will be staying (see page 3).

Important Schedule Notes

Arrival in Auckland 13 November—Your flight to New Zealand should route you through Auckland, New Zealand's capital and the city from which the group flight departs at the end of the program. **You must store your luggage**, except for one bag and a day-pack. We will be traveling on small-ish busses that do not have luggage space for extra bags. You have several options for luggage storage. There is a bag storage facility in the international terminal with which we have negotiated a half-price rate of NZ$110/bag for 17 days (the duration of the trip). Mention David Kendrick's name and the HWS/U Program when you check in. There are also public lockers in the international terminal. Small lockers are 90x42x55 cm for NZ$15/day. Large lockers are 90x42x87 cm for NZ$20/day. You might economize by sharing a locker of you can cram your bags in and are arriving and departing together. There are no lockers in the domestic terminal although there are a few small lockers available in the visitor's center near the airport. These are commonly full, but you are welcome to check them out if these options do not appeal to you.

Arrival in Christchurch 13 November—The group ticket you purchased will include a domestic flight to Christchurch on the afternoon/evening of 13 November. Once you arrive in Christchurch, you are responsible for your own supper and hostelry on the night of 13 November and breakfast the next morning.

Field Trip Departure 14 November—The program will rendezvous at **9 a.m. on Friday 14 November in Latimer Square** to depart for the field trip. Assemble on the corner of Hereford and Latimer streets near the Kukul Kwan Korean restaurant. The coach will be waiting there for us. There are a number of backpacker type accommodations near the park.

Program End 29 November—The program will formally end following the final exam on Friday 28 November. The program will provide breakfast for you the morning of 29 November and the bus will depart for the Auckland International Airport following breakfast if you wish to travel back to Auckland. You are responsible for all arrangements from this point on. You are welcome to depart the program any time after the final exam.

About the Guidebook

Please refer to the program web site (http://academic.hws.edu/Kendrick/OZ2008) for the most up to date information. While we have made every effort to ensure that all the logistic information in the guidebook is accurate, the guidebook was prepared in advance and sometimes things change. We will do our best to keep you updated, but check the website if you're in doubt. We'll make every effort to keep it up to date.

This guidebook is an informal publication designed to help you gain a deeper appreciation for the places we will visit and to provide helpful background. We are indebted to John Garver of Union College and Brooks McKinney of HWS for much of the information herein. Information in the guidebook has been assembled from a wide variety of sources, most of which have not been formally documented for you. Where we have found particularly useful references, they are noted.

Overnight Accommodation Information

November 14-15
Chalets at the Hermitage—Aoraki/Mount Cook National Park
www.mount-cook.com
+64-3-435-1809

November 16
Haast Beach Holiday Park—Haast Beach
+64-3-750-0860

November 17-18
Mountain View Top 10—Franz Josef
+64-3-752-0735

19 November
Mountain House Backpackers—Arthur's Pass
www.trampers.co.nz
+64-3-318-9258

20 November
North South Holiday Park—Christchurch
www.northsouth.co.nz
+64-3-359-5993

21-24 November
Discovery Lodge—National Park
www.discovery.net.nz
+64-0800-122-122

25-28 November
Kiwipaka—Rotorua
www.kiwipaka-yha.co.nz/rotorua/rotorua.html
+64-7-347-0931

Gear for the New Zealand Trip

For the New Zealand field trip you will not need any "evening out" types of clothes, lots of shoes etc. We will be outside for at least part of every day and some days we will be on long, all-day hikes in rough terrain. Our field work will go on regardless of weather, so you must be prepared for wet weather, cold weather, windy weather, intense sun and any combination of these. Several places that we will stay have laundry facilities, so you will be able to wash clothes during the trip. **Do not bring too much stuff!**

Day pack big enough for lunch, rain gear, water and a sweater or fleece
Field notebook
Field trip guidebook
Passport, tickets, travel documents
Pens and pencils
Hand lens if you have one
Camera, film or memory card, charger, plug adaptor (same as in OZ), extra batteries
Water bottles (minimum 2L)
Hiking boots
Sneakers or other close-toed shoes
Sunglasses
Sun hat or baseball cap
Lip balm with sunscreen
Sunscreen
Watch for keeping track of rendezvous times when you are exploring on your own
Sleeping bag
Rain jacket with hood, rain pants (recommended) It will rain and we will be out in it!
Gloves, winter hat
Heavy sweater or fleece to layer under rain jacket
2 pairs of long pants
1-2 pairs of shorts
At least one long sleeve shirt
T-shirts for about a week
7-10 days of underwear
Hiking and sneaker socks
Sleepwear (we will be in backpackers and other shared accommodations)
Towel
Toiletries
Medication and other personal supplies
Flashlight
Casual reading
Music player and headphones
Personal goodies (cards, musical instruments, knitting, hacky sack etc.)
Computer? You will not need your computer for course work

What to do in an earthquake?

Drop, take cover and hold. Move only a few meters to a safer place. Stay indoors until the shaking stops and you are sure it is safe to go outside. Stay away from windows, chimneys, and shelves with heavy objects. If you are in bed, stay there, put the pillow and blanket over your head to protect it from falling debris. If you are outside, drop to the ground in a clear spot away from buildings and power lines. If you are in a car, pull over and stay in the car. If you are in an elevator, stop at the nearest floor and get out. Be prepared! Keep your shoes and a flashlight within easy reach of your bed. Identify two possible exits before you go to bed. After the shaking stops, be alert to fire hazards and downed electrical lines. Expect aftershocks that may be as intense as the main event. If you are traveling with a group, gather together and move to a safe place.

Field Book Assignments

Here are the point values for the field book work:

Date	**Location**	**Points**
14 – 15 Nov	Aoraki	20
17 Nov	Knights Point, Monro Beach, Fox Glacier, Alpine Fault	15
18 Nov	Franz Josef	15
20 Nov	Arthurs Pass, Castle Hill, Torlesse Pullout	10
22-24 Nov	National Park Fence Diagram	20
25 Nov	Five Mile Bay, Wairaikei Geothermal Plant, Waimangu	15
26 Nov	Wai-o-tapu	15
27 Nov	White Island	10

Guidelines for Field Notes

There are two general elements to field notes: (1) observations and (2) interpretations. Observations are the details of where you went and what you saw while you were there. Interpretations describe what those observations tell you about the history those rocks represent.

Your field notes should emphasize observation. While we're in the field, take **detailed** notes on *your own* observations. We will be pointing things out along the way and discussing what it might mean, but those discussions won't cover everything. Although it is worthwhile to note what we say, this will not give you the whole story or full marks on field notes. Get in the habit of noting down the same set of observations at each stop.

At any field site, you should include the following information in your notes:

- Date, time, and weather conditions
- Name the stop. If there is some name already attached, use it. If not, choose something informative.
- Where is it? Include GPS coordinates if they're available. What cities, towns or parks are nearby? Is it by the side of the road? Etc.
- What is the landscape like? Describe the topography. Describe the outcrop itself and include a map and a sketch. They don't have to be artist-quality, just something that conveys what it looks like. **Make sure you include a scale and the orientation** (i.e., which way is north).
- Geologic context. If you know the formation names, include them. Likewise include the age, if you know.
- **What types of rocks are present? Provide detailed descriptions based on your own observations. Do this in a systematic way.** See the section below for suggestions on rock descriptions.
- Are fossils present? If there aren't any say so. If there are, note what they are. Describe them. Drawings are even better. Make sure to include a scale.
- What structural features do you observe? Are the beds horizontal? Tilted? Are there faults, folds, or joints? What are their orientations?
- What events do you observe? Are there beds? Are they all the same? If not, how are they different? Are there changes in sedimentation style? Can you see any cyclicity (repetitions)? Evidence of volcanic activity? Metamorphism? Faulting and folding? Can you tell the order of events? Something else?
- Anything else you deem interesting.

Rock Descriptions

What to say about the rocks? Developing a systematic checklist or outline to follow when you describe a rock gives you a routine to follow each time. Establishing a routine moves the effort out of the overwhelming category and into the okay, not so hard category. Here are some guidelines. Obviously some categories will apply to some kinds of rock and not to others. NOTE—THESE LISTS ARE NOT EXHAUSTIVE—THEY ARE GUIDELINES FOR THE KINDS OF THINGS YOU SHOULD LOOK FOR, BUT BE ALERT FOR THE UNUSUAL. DETAIL IS IMPORTANT.

- **Rock type**: Decide if the rock is sedimentary, igneous, or metamorphic.
    - *Igneous* – rock name, color, texture (crystal size), mineral composition, presence or absence of vesicles (bubbles), deformation of clasts (like squished or distorted pumice in ignimbrite), presence of volcanic glass, layering or other features in tephra, variation in outcrop scale, weathering.
    - *Sedimentary* – Is it clastic or chemical? Rock name, color, weathering, mineral composition, texture (grain size, sorting, and rounding), sedimentary structures (layers and their thicknesses, nature of contacts, e.g., flat, bumpy, hummocky, etc., presence of ripples, cross-bedding, etc). Are there fossils? If so, what kinds? How common?
    - *Metamorphic* – Rock name, color, texture (crystal size, crystal orientation), mineral composition, foliation, variation on outcrop scale.

Some igneous rocks

Phaneritic Rocks: Coarse-grained rocks with easy to see mineral grains

Quartz Content	Other Minerals	Rock Name
Quartz > 10%	Orthoclase >>Plagioclase	GRANITE
	Plagioclase >= Orthoclase	GRANODIORITE
Quartz < 10%	% Dark Minerals < 25%	SYENITE
	% Dark Minerals 25-50%	DIORITE
	% Dark Minerals > 50%	GABBRO

Aphanitic Rocks: Fine-grained rocks where only a few mineral grains are large enough to be easily seen (phenocrysts)

Rock color	Phenocryst Minerals	Rock Name
Light color (tan, pink, etc.)	Quartz and Orthoclase	RHYOLITE
Intermediate colors (gray, brown, etc.)	Plagioclase, Pyroxene, Hornblende (No Olivine)	ANDESITE
Dark colors (black, dark gray, etc.)	Olivine, Plagioclase, Pyroxene	BASALT

Volcaniclastic Rocks

These rocks are a hybrid category – they are igneous in origin but also feature elements of sedimentary rocks. Tephra deposits fall from the air, for example, and may show graded bedding, for example. Ignimbrites, sometimes called welded tuffs, originate as pyroclastic flows and may show evidence of that flow. They also show evidence of the fusion of the material and sometimes also the deformation of their constituents – pumice, for example, can be squeezed and contorted as a result of the heat and pressure of the material when it is deposited.

Metamorphic Rocks

Foliated Rocks: Rocks with well-developed alignment of planar minerals (*i.e.* they show some kind of banding or layering of minerals). Protolith means what the rock started out as before it was metamorphosed.

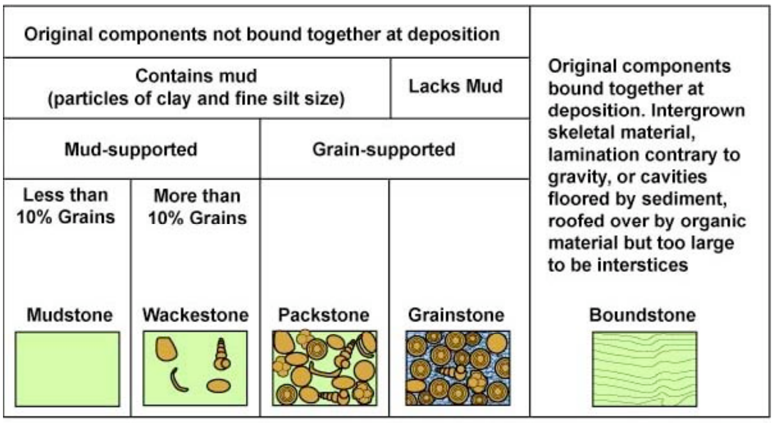
Foliation Type	Grain Size	Rock Name	Protolith (parent rock)
Micaceous – aligned mica crystals	Can't see grains, dull	SLATE	Shales, mudstones, arkoses
	Can't see grains, shiny	PHYLLITE	
	Visible mica grains	SCHIST	
Aligned hornblende crystals	all sizes	AMPHIBOLITE	basalts, gabbros
Gneissic layering (dark-light banding)	all sizes	GNEISS	granite, rhyolite, arkose

Granoblastic Rocks: Unfoliated (unlayered) rocks lacking aligned oriented grains.

Mineral	Rock Name	Protolith
Calcite, Dolomite	MARBLE	Limestone, Dolostone
Quartz	QUARTZITE	Quartz Arenite (pure sandstone)

Sedimentary Rocks

Describing carbonates



C. G. St. C. Kendall, 2005 (after Dunham, 1962, AAPG Memoir 1)

Naming clastic rocks

Dominant Grain Size	Sediment Name	Rock Name
>2 mm	Gravel	Conglomerate, Breccia
2 - 1/16 mm	Sand	Sandstone
1/16 - 1/256 mm	Silt	Siltstone
<1/256 mm	Clay	Shale

You can't see clay-sized particles. Silt is almost all too small to see (though you can feel it as grit on your teeth). Therefore, if you can see the grains, you're looking at sandstone or greater.

An Overview of New Zealand Geology

Today's New Zealand is just the tip of a larger, mostly submerged continental fragment (called Zealandia) that, itself, was once part of the Australian continent and before that part of the great continent of Gondwana. Zealandia includes the highlands of modern-day New Zealand, plus the Challenger Plateau and Lord Howe Rise to the northwest, and Chatham Rise and Campbell Plateau to the southeast. All of these regions are composed of basically the same rocks (McSaveney and Nathan 2007), demonstrating that they have basically the same history. The key to understanding New Zealand's geology is remembering that New Zealand is the product of tectonic forces. Rocks exposed at the surface today have been near a plate margin for most of their history (note some exceptions below), which gives this small island a complex geology. This also makes New Zealand an ideal place to see a lot of different types of geology in a small area.

New Zealand's Tectonic Provinces

New Zealand can be divided into five tectonic provinces that reflect the timing, style and rate of deformation (Fig. 1, Aitken 1996). The **Nelson-Westland** tectonic province is located in the northwest and extreme west of the South Island. It contains New Zealand's oldest rocks and preserves the geologic connection with Gondwana, as some rocks found here have very similar counterparts still attached to Antarctica and Australia (Aitken 1996). This region also contains a set of faults on which major earthquakes have occurred. Movement on these faults averages about 1 mm/year (Aitken 1996).

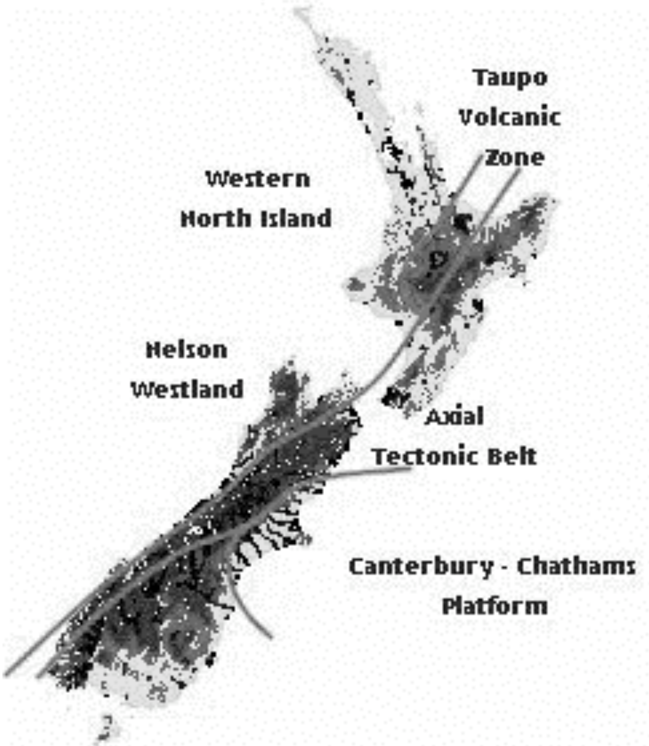


Figure 1: Five major tectonic zones in modern-day New Zealand. Each zone reflects a different style or rate of deformation based on the forces most active in that region. The Axial Tectonic Belt is characterized by shear deformation with a significant vertical component that varies in magnitude from south (high) to north (low). The Taupo Volcanic Zone is dominated by subduction-related volcanism and crustal thinning and extension. The Nelson-Westland, Canterbury-Chathams, and Western North Island regions are less tectonically active at present.

In contrast, the **Axial Tectonic Belt** (Fig. 1) is by far New Zealand's most active region. It extends across both islands, from Fiordland in the southwest through the Southern Alps, Marlborough, and the eastern half of the North Island. It includes the most important fault systems in New Zealand, particularly the Alpine Fault bounding the Southern Alps to the west, the Hope Fault in Marlborough, and the North Island Shear Belt (Aitken 1996). Because the collision between the Pacific Plate and the Australian Plate is oblique here, a tremendous amount of shear stress is generated along with compression. Thus, almost all of the faults active in this region produce shear (strike slip motion) as well as compression (reverse motion). This combination of forces along this system can produce intense seismic activity. Movement along the Alpine fault averages 35 mm/year; it produces major quakes every 250-400 years with average movements of 8 m horizontally and 12 m vertically (Aitken 1996). Based on mapping of rocks on either side of the Alpine Fault, geologists estimate that it has moved 480 km in the last 20 Ma (McSaveney and Nathan 2007). Movement along the Marlborough fault system has a slightly lower rate of 15-25 mm/year. On the North Island, rates of movement are more difficult to measure because the fractured rocks are buried beneath a thick blanket of more recent volcanic debris. However, observations of the topography show that horizontal, rather than vertical, movement dominates here, owing to the angle of the plate collision.

The **Taupo Volcanic Zone** (Fig. 1) is a region of crustal thinning caused by heating and extension associated with subduction under this region (Aitken 1996). Where continental crust generally averages about 35 km thick, the crust under the Taupo region is only about 15 km thick. This reflects significant heat generated by the rapidly subducting Pacific Plate. As this heat rises through the crust, it causes the crust to expand, rise, thin and pull apart to a small degree. This, topped by the volcanoes themselves, produces the spectacular topography found in the Taupo Volcanic Zone.

The **Western North Island** and **Canterbury-Chathams Platform** (Fig. 1) are relatively quiet compared to other regions. Fault movement in the Canterbury-Chathams region averages less than 1 mm/year (Aitken 1996), while few recently active faults are known from the Western North Island.

Tectonic History

The oldest rocks exposed in New Zealand today were formed on an ancient continental shelf adjacent to present-day Australia and Antarctica (McSaveney and Nathan 2007). These rocks began their lives as sediments washed down from mainland Gondwana during the Cambrian through Devonian periods (refer to the geologic time scale at the end of this guide for age dates). During the Late Devonian and Carboniferous, subduction developed to the east of the Gondwanan passive margin, compressing, metamorphosing, and folding these sediments into the near vertical orientations observed today (McSaveney and Nathan 2007). What started as clastic deposits are now schists and gneisses. In some places, metamorphosing temperatures grew so high that the ancestral sediments actually melted, recrystallizing as the granites and diorites exposed along the west coast of the South Island from Fiordland to Nelson. These rocks are hard and resist weathering and erosion, producing Fiordland's spectacular steep-walled valleys.

At about 200 Ma, subduction ceased and a passive margin redeveloped along the eastern coast of Gondwana (Fig. 2). Sediments once again began to stream off the Gondwanan highlands, producing the Torlesse greywackes (dirty sandstones), which are thousands of meters thick and cover more than half of the New Zealand land mass (McSaveney and Nathan 2007). In most places, the sandstone alternates with darker mudstone, indicating that these were produced in a deep-water continental shelf and slope environment where submarine landslides producing turbidity currents deposited most of the sediment. Mineralogical analysis of these sediments show that they are rich in quartz and feldspar, similar to the granites of northeastern Australia, the likely source rocks from which they were weathered (McSaveney and Nathan 2007).

While the greywackes accumulated far off shore, volcanic sediments were deposited in the shallower coastal waters. They form a band nearly 1,000 km long along the eastern margin of Gondwana. The presence of identical volcanic rocks in Australia, western New Zealand and (presumably) Antarctica show how the continents were joined during the Mesozoic.

Beginning about 150 Ma (Fig. 2), the passive margin was again disrupted by the initiation of subduction to the east of Gondwana's passive margin. As oceanic crust was dragged under the continent's margin, thick stacks of shelf sediment were scraped off as steeply dipping, overlapping slabs that sometimes included a bit oceanic crust. Torlesse greywacke was also buried up to 10 km and heated to over 300°C to form the Haast schists on the western side of the Southern Alps (McSaveney and Nathan 2007). It was during this metamorphic event that the South Island's jade resources were formed. As before, some rocks were heated so much that they melted, producing the Cretaceous-age granites exposed in Abel Tasman National Park in the northwest of the South Island.

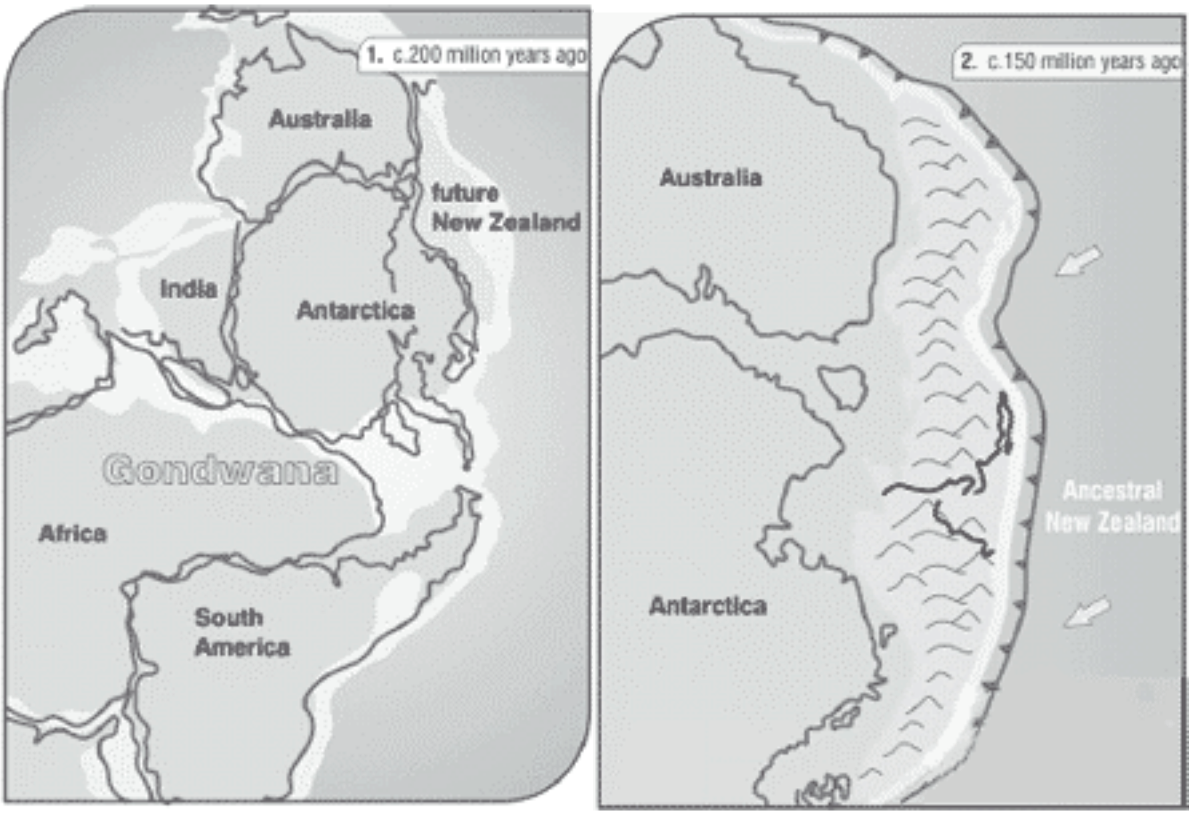


Figure 2: Gondwana approximately 200 Ma (left) and 150 Ma (right). Sediments that formed New Zealand first began to accumulate on the passive margin to the east of Gondwana. When subduction developed to the east of this margin, these sediments were compressed, metamorphosed, folded and uplifted to form new land along this eastern margin.

By the middle of the Cretaceous Period, a long chain of mountains once again stretched several thousand kilometers along the eastern coast of Gondwana, including both Australia and Antarctica. In the moderate temperate climate of the day, erosion began to wear them down almost immediately, shedding a blanket of sediment out across the coastal lowlands and onto the new continental shelf. In some places, the lush vegetation was preserved as coal and the floodplain sediments entombed dinosaurs and a variety of marine reptiles (McSaveney and Nathan 2007).

At the same time, a rift began to develop along the eastern margin of Gondwana, well inland of the newly-formed coastal mountains. Rift-associated volcanoes spewed mafic rocks onto the surface. These are today visible in Mount Peel, the Malvern Hills and Mount Somers in Canterbury. By about 85 Ma, the ocean had flooded the rift (Fig. 3) and New Zealand was isolated from Australia. Seafloor spreading continued for about 30 Ma and mysteriously stopped, leaving the modern Tasman Sea (McSaveney and Nathan 2007).

A marine section at Woodside Creek in Marlborough preserves a thick clay layer with high levels of the element iridium, marking the moment in time when a large meteor struck Earth (Alvarez et al. 1980) and precipitating the extinction of the non-avian dinosaurs and heaps of other animals and plants on land and in the sea. The ecological havoc wrecked by this event is also witnessed in New Zealand in the form of a superabundance of fern spores just above (after) the impact layer (Vajda et al. 2001, Hollis 2003). A similar layer is observed in North America and is widely interpreted to indicate a disturbance flora rich in ferns that colonized the landscape after the impact catastrophe (Tschudy et al. 1984, 1986).

Although the Woodside Creek sediments were marine, their pollen content shows that land was nearby. Terrestrial rocks in Canterbury preserve the leaves of some of the plants responsible for this pollen. Since leaves are so essential to the functioning of plants, they are commonly highly adapted to the particular environments in which they are found. As a result, fossil leaves can be used to reconstruct climates of the past. Work by Elizabeth Kennedy showed that the diversity of angiosperms (flowering plants) declined significantly following the Cretaceous-Tertiary extinction, but climate didn't change too much (Kennedy 2003). New Zealand remained cool to mild (mean annual temperature 6-12°C, today's MAT ranges from 10-16°C depending on location) and temperate with abundant rainfall throughout this period of change.

While a significant portion of the Zealandia was above sea level during the early phases of rifting from Gondwana, as rifting slowed and eventually ceased, the continent cooled and sank into the mantle below, submerging large regions. The Late Cretaceous and Paleocene terrestrial rocks of Canterbury show clearly that this part of present-day New Zealand was still above sea level, but a detailed look at the sediments shows that by Oligocene time, less than one third of present-day New Zealand was above the waves. What land remained was isolated into a serious of relatively small islands (McSaveney and Nathan 2007). Many of these islands were capped with low-lying coastal swamps, from which most of New Zealand's coal comes. Between the islands, carbonates (limestone) accumulated in shallow seas (McSaveney and Nathan 2007).

This sinking may partially explain the paucity of animal diversity on New Zealand. The only native mammals, for example, are bats, that could disperse to the island relatively recently. Instead, New Zealand's terrestrial fauna is rich in birds, both flying and flightless. Some members of the ratite (emu) family, such as the moas, were likely flightless when Zealandia rifted from Gondwana. Others likely lost flight after immigration. Nonetheless, the extreme fragmentation of New Zealand's land mass may explain some of its diversity patterns. A good terrestrial fossil record is needed to flesh out this story. However, such a record—if it exists—has yet to come to light.

By the end of the Oligocene, the modern configuration of plate boundaries had been established (Fig. 3). To the north, the Pacific Plate was sinking beneath continental rocks of the Australian Plate. The Pacific Plate was rotating relative to the Australian plate producing shear stress that initiated the formation of the Alpine Fault. Despite the dominant shear motion, significant compression still occurred, lifting much more land above sea level and exposing more of modern New Zealand. Uplift continues today and appears to be accelerating. The land east of the Alpine Fault, for example, is rising approximately 2 m per century and Aoraki was below sea level less than a million years ago. However, erosion is generally keeping pace with this rapid uplift and the mountains themselves to not appear to be growing.

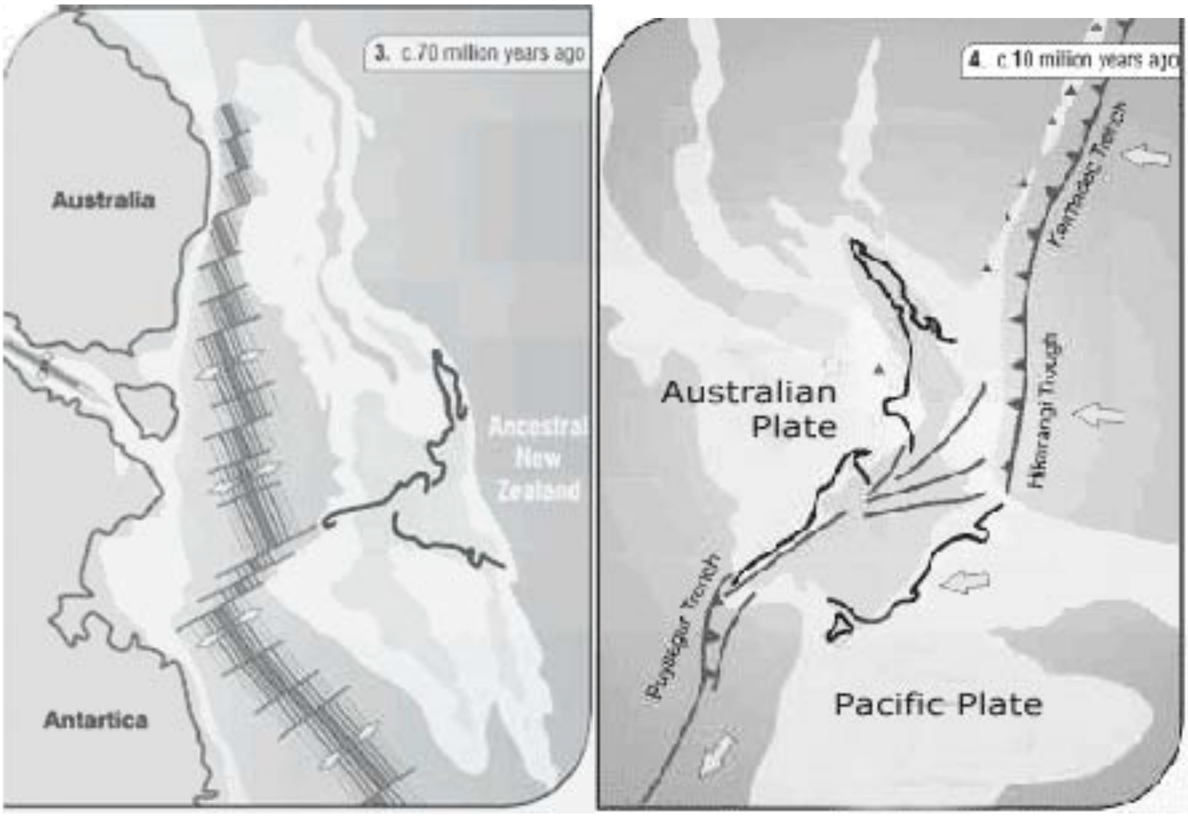


Figure 3: Rifting (left) began between eastern Gondwana (Australia and Antarctica) about 85 Ma and broke off the large piece of crust on which New Zealand sits (gestural black outline). By about 10 Ma, the modern plate boundary configuration (right) had developed, with New Zealand forming the transform link between opposite-dipping subduction zones.

Volcanic activity initiated about 13 Ma in the south of the South Island. The Banks and Otago peninsulas were formed by basaltic volcanism, and Dunedin sits in the eroded hulk of an ancient volcano (McSaveney and Nathan 2007). Some of the material erupted around Dunedin is classified as ultramafic (a rock called dunite, after Mt. Dun, in the Nelson area of the South Island), representing material that originated in Earth's upper mantle. This is one of only a handful of places on Earth where this type of material is exposed.

During the last 2 Ma, volcanism has shifted north to the Taupo Volcanic Zone. Along with the shift in location was a change in volcanic style to a more typical intermediate magma composition characteristic of subduction-related volcanoes. Some of these volcanoes, such as Taupo itself, Rotorua, and Okataina have erupted in violent super-volcanoes, the effects of which were felt worldwide. Ash from the Taupo caldera has been found on the Chatham Islands (McSaveney and Nathan 2007) and material injected high into the atmosphere reddened skies and cooled weather in the Northern Hemisphere (Wilson et al. 1980). Simultaneously, andesitic volcanoes like Tongariro, Ngauruhoe, Ruapehu and Taranaki erupt more quietly—although still with explosive force—and build their splendid stratocones. The Tongariro volcanoes have been built within the last 260,000 years (McSaveney and Nathan 2007).

And with fire also came ice. Beginning about 2.6 Ma, global climate cooled sufficiently to plunge Earth into a series of "Ice Ages". During glacial intervals, mountain glaciers accumulated in the Southern Alps from Fiordland to Nelson on the South Island, and on the central volcanic highlands on the North Island. Fed by abundant snowfall at high elevations, the glaciers pushed their way to the sea, grinding up the landscape as they went. They advanced and retreated numerous times during the ensuing time, leaving wide swaths of glacial debris and some of New Zealand's most spectacular scenery in their wake. During interglacial times (such as the present), rivers took over the work of moving sediment. As climate warmed and rivers took over, thick blankets of sorted sediment were deposited to the east of the Southern Alps. Slowly, the Canterbury plain built out to the east, eventually engulfing the offshore Banks volcano to form a peninsula. The work of these rivers continues today, which more material being spread with every spring snowmelt and summer rain.

The South Island

Figure 4: The South Island of New Zealand showing our travel route and the location of overnight stops.

Day 0—Thursday 13 November. Transit from Australia to Auckland, New Zealand. Store your extra luggage if you have any and catch your flight to Christchurch. If the weather is clear, you will have a spectacular overview (literally) of New Zealand geology on your flight. As you gain altitude out of Auckland, look back and notice the many small conical hills scattered throughout the city. These are all small volcanoes. Although none, except Rangitoto in the Auckland Harbor[1], have erupted since humans arrived in New Zealand about 800 years ago, they are still considered active. As you fly southeast, you'll cross a relatively low and eroded landscape which was the setting of The Shire in Peter Jackson's LOTR movies. Then you'll cross the line of volcanoes and volcanic calderas that mark the surficial evidence of tectonic subduction far beneath the island. Note the contrast between the rounded and conical volcanic mountains of the North Island, and the jagged fault block mountains of the Southern Alps on the South Island.

Southeast of Christchurch (Fig. 4) is the Banks Peninsula, which is composed of two extinct, overlapping and deeply-eroded basaltic volcanoes. The eastern of these is the Akaroa volcano, the western is called Lyttelton. Both are examples of hot-spot volcanoes erupting onto the interior of a plate (Sewall et al. 1992). Suggate (1978) describes them as "erosional calderas" in which wind and rain have breached the weak, innermost lava and tephra deposits that formerly composed the highest portions of the volcanoes, leaving large, bowl-shaped structures, perfect for the harbors of Akaroa and Lyttleton and echoing the process evidenced by the Tweed Volcano at Lamington National Park in Queensland. (These are very different from the felsic collapse or explosive calderas that we will see in the Taupo Volcanic Zone on the North Island.)

As you approach Christchurch, you'll pass over the Canterbury Plain, a broad east-dipping surface between the Banks Peninsula and the faulted and folded rocks of the Southern Alps. The area is intensively farmed and provided the locations for Rohan in LOTR. The landscape is underlain by Quaternary gravels deposited as coalescing sedimentary fans by braided streams carrying sediment eastward from the Southern Alps. In the last 2 Ma, the buildup of these deposits has shifted the eastern shoreline approximately 10 km. Both erosion and transport were enhanced during glacial times, when glaciers extended down nearly to the western margin of the plains (Beanland 1987). In periglacial times, up to 60 m of windblown loess was deposited on top of the gravels, significantly increasing the fertility of the area. With decreased sediment supply during the current interglacial, streams like the Wimakariri River, which flows through Christchurch, are now cutting into the gravel plain. If you get a good view of the plain from the air, you can imagine it being deposited as a blanket of clastic debris spreading out from the rising mountains to the west.

You will have the evening free in Christchurch. **You will be responsible for your own food and hostelry until you meet the group tomorrow morning.** After this time, your housing, meals and transport will be covered until we return to Auckland after the conclusion of the program.

Day 1—Friday 14 November. We will rendezvous with the bus at 9 a.m. in Latimer Square, on the corner of Hereford and Latimer streets. Please be there on time. We will take a head count before we depart, but we will not wait for you if you are late. If you miss the bus, it

[1] Rangitoto was born about 800 years ago. There are several places where human footprints are preserved in the now-rock-hard volcanic ash. Therefore, we know the ancestors of the Maori had already arrived on the North Island and had gone out to explore the new piece of land that popped up in their midst. Today this little volcano is a park with some really wonderful hiking trails. If you plan to hang out in Auckland, it's well worth a day trip.

will be your responsibility (and expense) to catch up with the group. If you have travel difficulties, please contact Profs. Arens or Kendrick as soon as you realize there is a problem. We will do our best to help you get together with the group.

We will depart Christchurch and drive southwest on SH1 toward the coastal town of Timaru. Before it was established as a whaling station in 1839, Timaru was a Maori camp – Te Maru, "The Place of Shelter". Interestingly, there appear to have been no permanent Maori settlements on the South Island, although it was visited frequently and occupied for extended periods. Anthropologists attribute this to the fact that a Maori staple crop, sweet potato (no relation to ours, which are from the New World) could not grow in the cooler southern climate.

Between Geraldine and Lake Tekapo, we enter the Mackenzie Basin, an area characterized by thrust fault mountains and broad valleys filled with glacial debris. We will stop at the Aoraki Lookout at Lake Pukaki for lunch. After lunch, we will continue on to Mount Cook Village.

Aoraki (3755 m) is New Zealand's—in fact Australasia's—highest mountain. It takes its name, "Cloud Piercer", from an ancestral Maori god. It was named Mount Cook, after the explorer James Cook, by Captain Stokes of the survey ship HMS *Acheron*. Both names are still in use, but most modern Kiwis prefer the original, Maori name. Aoraki was first climbed in 1882 by Tom Fyfe, Geogre Graham and Jack Clarke. The first woman to climb Aoraki was Freda du Faur in 1913. Edmund Hillary and Tenzing Norgay climbed the mountain in 1948. Hillary, a Kiwi, credits the mountain for teaching him vital skills that allowed him to be the first, again with Norgay, to conquer Mount Everest in 1953. Aoraki is still the focus of mountaineering. Look inside the main lodge for a book commemorating those who have lost their lives climbing here—note the date of the most recent entry.

Arriving at Mount Cook Village, we will check in as quickly as possible, gear up and head for the glaciers. Remember to carry your fleece or sweater, hat, rain gear, flashlight and water. Wear hiking boots.

Hooker Glacier Trail Walk (6-7 km, 4 hours return)
This is a spectacular trail that includes several swing bridges over roaring glacial streams. The trail traverses the most recent recessional moraine of the Hooker Glacier. Along with way we will cross over several moraines, including the lateral moraine of the Mueller glacier that enters the Hooker Valley from the west (left side as you go up the trail). The trail ends at a small lake behind the Hooker recessional moraine. Small icebergs are often rafted down to this end of the lake.

IMPORTANT: Regardless of what the sky looks like when we depart, carry your fleece, hat, raingear and a flashlight at all times. Watch the weather and the time. Depending on light and weather conditions when we arrive, we will announce a "turn around time" at the trail head. You *must* honor this time, even if you do not make it to the trail's end. If weather threatens, we expect everyone to turn around as well. Sunset on this date is approximately 8:30 p.m. and hiking after dark is unwise. Use good judgment for safety.

Day 2—Saturday 15 November. The Aoraki region has some of the highest mean annual precipitation totals in New Zealand. Westerly winds from the Tasman Sea, coupled with a strong orographic effect result in abundant moisture on the crest of the Southern Alps (Fig. 5). This, in conjunction with wind loading of cirques on the eastern side of the Main Divide, nourishes some of New Zealand's largest extant glaciers. These glaciers have waxed and waned following the beat of climate change in the southern Pacific.

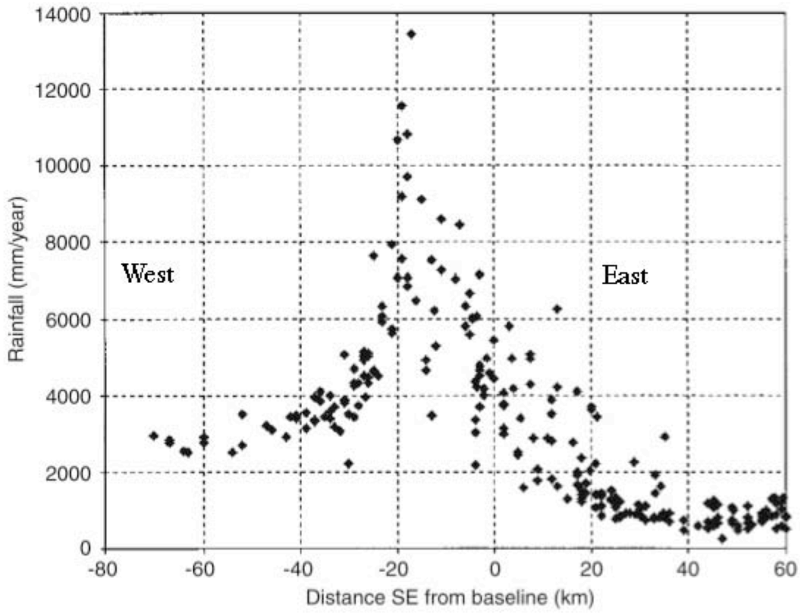


Figure 5: The orographic effect of the Southern Alps. Peak precipitation can approach 14 m/year! Note that rainfall is highest on the western side of the divide (baseline zero). This precipitation nourishes glaciers on both sides of the divide (data from Lowell et al., 2005).

Unlocking the timing of climate change involves dating the waxing and waning of glaciers by examining the ages of the moraines they left behind as they retreated. Dating moraines is challenging because there is often not much in the way of organic material preserved within them, making carbon-14 dating of little use. In addition, the youthfulness of late Holocene moraines means that they have not yet had time to accumulate significant quantities of cosmogenic radionuclides that can be used to date these deposits.

One technique, known as lichenometry, is both accurate and simple to apply. It is particularly useful for dating moraines deposited over the last several centuries or so [see \Lowell, 2005 #4, at the end of this guidebook]. Lichen is a microbial community composed of a symbiotic relationship between a fungus and an alga or cyanobacteria. Lichens tolerate very harsh growing conditions and commonly are the first to colonize rocks in glaciated or volcanic terrains. Growth rates of the crustose lichen *Rhizocarpon geographicum* vary greatly (0.02-2 mm/yr) in this area, depending on substrate and available moisture and individual thalli (the lichen body) of *R. geographicum* appear to live for hundreds of years. The premise behind lichenometry when applied to late Holocene glacial deposits is that lichens will colonize boulders on a moraine surface shortly after those boulders are deposited. With time, the diameter of the early colonizers will increase and they'll be joined by new recruits of lichens that will continue to colonize available space on boulder surfaces. Only those early colonizers have sizes that reflect the total time since moraine formation and it is those thalli that we will need to find on moraine surfaces.

Lichenometry can provide a means of correlating moraines found in nearby valleys, but its real potential is in dating the age of stabilization of moraine surfaces. To achieve this potential, a growth curve needs to be developed for moraines in a region, where conditions are assumed to be similar, although not constant through time. Lowell and colleagues (2005) accomplished this by measuring the size of *R. geographicum* thalli on surfaces whose ages were known by other means (e.g., dendrochronology, radiocarbon dating, or historical observation). One such growth curve for the Aoraki region is shown in Figure 6.

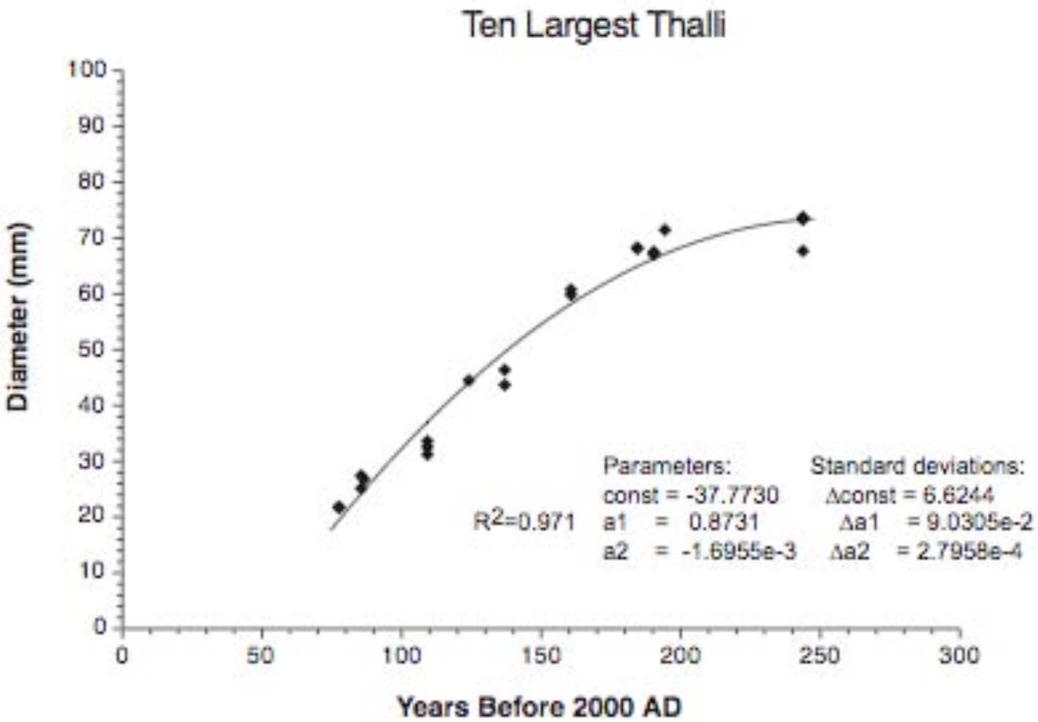


Figure 6: Age calibration for the size of *Rhizocarpon geographicum* for the Aoraki region of New Zealand (figure 7 from Lowell et al., 2005).

Glacial valleys in the Southern Alps contain numerous small moraines that were deposited within the last several millennia (Winkler 2000, 2004). A copy of Winkler (2000) is available at the end of this guidebook. Mapping these discontinuous moraines determines the configuration of past ice margins and dating these ice marginal positions will be the focus of a class project on the Hooker glacier. We will begin by identifying and mapping the location of moraines in the Hooker valley. Then, several groups will age date the moraines by counting the ten largest lichen thalli on individual or adjacent boulders. Using the curve in Figure 6, you'll then estimate the age of the moraine. You will repeat the dating procedure for ten boulders, taking the average of these replicates to establish an average age and standard error for your estimate.

Day 3—Sunday 16 November. We will depart Aoraki and traverse Haast Pass to the West Coast. This is a long drive (5-6 hours) through increasingly spectacular scenery toward better-watered country (Fig. 7). Although we will finish the day only about 100 km as the crow flies from our starting point, we will have to drive about five times that distance to get there. We start in the dry lands around Twizel (annual precipitation 622 mm), have lunch in Wanaka (annual precipitation 2000 mm), then cross the Southern Alps through Haast Pass (annual precipitation 4500 mm), and wind up on the west coast at Haast Beach. By way of reference, annual precipitation in upstate New York is about 900 mm. Precipitation patterns are the result of prevailing westerlies from the Tasman Sea striking and being lifted over the Southern Alps. This generates orographic rain on the West Coast, while the area east of the Southern Alps lies in their rain shadow. Here, sinking air that has already lost most of its moisture provides most of its precipitation. As we emerge from the steep mountainous terrain of the Southern Alps onto the west coastal plain, we will also cross the Alpine Fault and in so doing, drive from the Pacific Plate onto the Australian Plate. Cool!

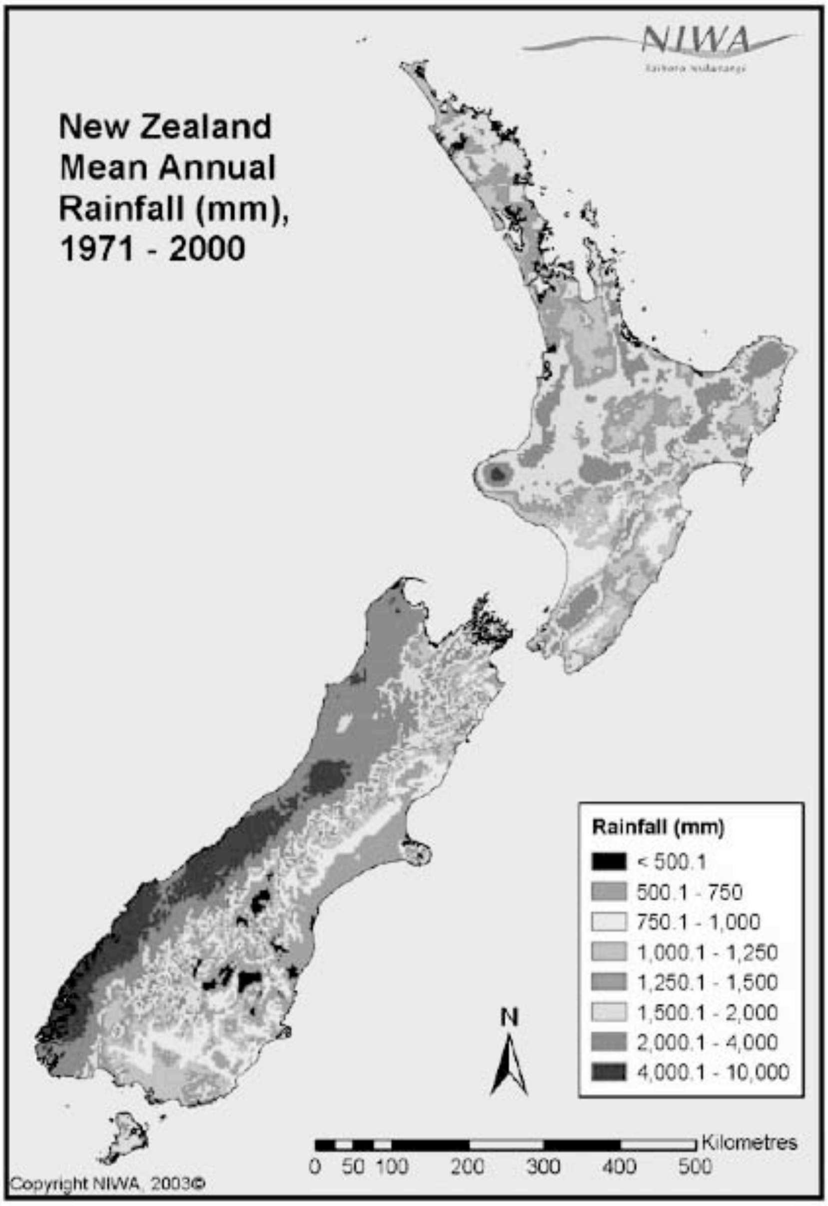


Figure 7: New Zealand mean annual rainfall (mm), 1971-2000. Note orographic effects on distribution of rainfall.

The Haast Pass highway we will travel follows the same route used by the Maori traveling to the West Coast in search of pounamu (nephrite jade). The route's name, Tiora-patea, means "the way is clear". Gold prospector Charles Cameron is thought to be the first person of European descent (pakeha) to travel the pass in 1863.

The trip down the west side of Haast Pass offers a spectacular look at this ancient Gondwanan vegetation. Although both sides of the pass are covered in southern beech (*Nothofagus*), the vegetation within the forests differs significantly. On the drier east side of the Southern Alps, mountain beech predominates, with a sparse understory of small trees and shrubs. In the wetter forests on the western side, silver beech dominates with tree ferns and podocarps increasingly important at lower, and warmer elevations.

Arriving at Haast Beach, we will check in to our accommodations, have an early dinner, then travel 31 km north of Haast to Monro Beach. Bring a flashlight and bug spray if you use it. The sand flies are a bit ferocious on the beach. Here, we will take an easy 5 km round trip hike down to Monro Beach, one of the places to see endangered Fiordland crested penguins. These penguins are endemic to the West Coast of the South Island from here south, but only about 3000 breeding pairs are thought to remain. The birds maintain a breeding colony at Monro Beach from July to November; the best time to view the penguins is just before sunset, when the birds return from the day's fishing at sea and settle into their burrows for the night.

IMPORTANT: The population is small and this is one of only a handful of healthy rookeries. The penguins are *very* sensitive to human disturbance. There are signs on the beach that ask you not to proceed further toward the nesting burrows. ***Obey them!*** If you do not, you are stressing the birds, perhaps forcing them back to sea where they are unlikely to survive over night. They will see you from the surf before you see them and they will turn around. We have few opportunities to directly impact the survival of an endangered species. This is one of them. Make good choices and use your zoom lens.

Day 4—Monday 17 November. We will begin the day with a short walk through the forest just across the street from the Haast Beach Holiday Park. This is a good opportunity to take a closer look at the strange vegetation of the West Coast. The forest here resembles the dinosaur-age forests of the American west: dominant podocarp conifers with small, shrubby flowering plants in the understory. You can also see stands of flax plants. These became the base of one of New Zealand's first exports: flax fiber for making linen. We will then board the bus to begin the trip north to Franz Josef.

Stop 1: Knights Point Lookout
In addition to taking in the view here and using the restrooms, we want to take a close look at the outcrop exposed by road construction.

<u>Notebook Assignment</u>: Make a detailed and accurate sketch of this outcrop and annotate your sketch with some explanations of what has happened here.

Stop 2: Monro Beach Again
We will return to Monro Beach, this time to have a better look at the rocks exposed along the south end of the beach.

<u>Notebook Assignment</u>: Take a careful look at these sedimentary rocks, describing the outcrop as a whole in your notebook. These rocks have been strongly deformed—how can you tell? Is it possible to determine which of the exposed strata are younger or older? In other words, which way is up? Sketch any evidence you find for up-directions. Finally, briefly describe the important events that must have been necessary to produce this outcrop.

Stop 3: Fox Glacier
This is the first of two West Coast glaciers we will look at, the other being Franz Josef glacier tomorrow. From the parking area, we will walk up a short trail to the glacial snout. DO NOT CROSS ANY BARRIERS, DO NOT CLIMB ON OR APPROACH THE GLACIAL FRONT! Things to note in your notebook include the color of the ice and the debris covering

it, the melt water stream emerging from the snout, the character of the outwash sediments, striations on the overhanging valley walls, and evidence of higher stands of the glacial ice, especially lateral moraines. If the weather is good, you may be able to look up the glacier to see the snow fields below Aoraki. Both Fox and Franz Josef glaciers extend down nearly to sea level, while the glaciers on the east side of the Southern Alps are confined to high elevations (recall the hike up to Hooker Glacier). While the temperatures on both sides of the Alps are similar, precipitation patterns are not. The extension of west coast glaciers to lower elevations reflects not cooler temperatures, but the greater supplies of winter snow delivered to the western slopes. Recall the glacial budget we discussed in lecture. In what other ways can you compare and contrast the Hooker and Fox glaciers?

<u>Notebook Assignment</u>: Make the observations mentioned above and describe them in your notebook. Any other observations will garner higher marks.

Stop 4: Hare Mare Creek, Alpine Fault Exposure
The Alpine Fault is exposed 200 m up the creek in the south bank. We will walk up the north bank to view the fault. Beanland [, 1987 #3] describes the exposure as mylonite thrust over gravel. Mylonite is a fine-grained metamorphic rock that commonly has very fine banding of different colors. Mylonite only occurs in shear zones like the Alpine Fault, where tremendous amounts of stress are placed on the rocks right around the fault. This stress causes minerals to reform and align in bands to essentially take up less space.

<u>Notebook Assignment</u>: Sketch this exposure, indicating the features that mark it as a fault zone. This is about as close as you can get to seeing a boundary between two plates. Do you notice any difference in the rocks on either side of the fault? As you consider the fault and the transform boundary it represents, remember that there has been more than 450 km of slip along this fault.

Day 5—Tuesday 18 November.

Stop 1: Franz Josef Visitor Center
Our first stop this morning will be the Franz Josef Visitor Center. Take your notebook and make some notes on two aspects of the local geology: 1) the Alpine Fault and the earthquake hazards it presents, and 2) the historical record of ice advance and retreat for both the Franz Josef and Fox glaciers. Also, be on the lookout for signs of the trace of the Alpine Fault. We will cross it at some point between the Holiday Park and the glacier.

Stop 2: Waiho River Bridge and Franz Josef Glacier Access Road
The Waiho River drains the Franz Josef Glacier (with contributions from other streams) and is considered a major flood risk by the New Zealand Ministry of Civil Defense and Emergency Management. Below the canyon mouth (west of the highway bridge), the river is partially constrained by the Waiho Loop, a recessional moraine that forms a prominent forested ridge. Between the glacier front and this moraine, the riverbed is aggrading (depositing sediment) with glacially derived sediment. Between 1940 and 2002 the river bed rose by more than 10 meters, lifting it above adjacent areas and creating significant flood risks. This risk is heightened by periods of glacial outburst—sudden, copious releases of water from the glacier margin. As you stand by the river, compare the elevation of its bed to

that of surrounding areas and the potential flood risk will become clear. Make a sketch and notes in your notebook.

Stop 3: Franz Josef Glacier
We will spend a couple of hours walking up the valley across glacial outwash to the base of the Franz Josef Glacier. There will be two types of features to look at. The first and most obvious are glacial ones. You will see outwash, glacial striations, roche moutonees, and variety of other glacial features. Second, you will see evidence of metamorphism and deformation preserved in the high-grade schists that have been uplifted by Alpine Fault and deeply eroded by the glacier.

Franz Josef Glacier: This active glacier is fed by extensive snowfields on the western slopes of the Southern Alps and here extends down nearly to sea level. The Franz Josef Glacier and the Fox Glacier just to the south are very rapidly moving glaciers—a meter a day is typical. This makes the ice front very unstable and potentially dangerous. We will walk from the car park to a series of large schist outcrops-roche moutonees where we can see the glacier and the braided outwash stream—the Waiho River—coming off the glacier. These large outcrops were the western limit of the glacier as recently as 1900. From there you can walk up the valley to the snout of the glacier. DO NOT CROSS ANY BARRIERS—DO NOT WALK/CLIMB ON THE GLACIER!

As you walk, note the types of sediment being carried by the stream, the channel style, features along the valley walls, and the schist making up those walls. Look in particular for evidence of larger volumes of glacial ice in the past.

Alpine (Haast) Schist: There are beautiful, glacially polished outcrops of schist through the valley walls as you walk from the car park toward the glacier. These rocks started out as sedimentary rocks and minor volcanics that have been altered by high heat and pressure. Little and colleagues (2002) mapped a series of textural changes in the schists here, including strongly foliated mylonites (sheared rocks) directly along the fault. In the exposures near Sentinel Rock you should be able to find garnet porphryoblasts as well as small isoclinal, refolded folds (F2 folds for you structural geology fans). The garnet-biotite-oligoclase assemblage corresponds to metamorphic T and P estimates of approximately 6-9 kbars (rocks buried 18-27 km deep in the crust) and 415-620°C and a metamorphic field gradient of 14°C/km (Grapes 1995).

Time and weather permitting, we will walk up the valley trail for a look at the active surface of the glacier. The trail is uphill and skirts the edge of the valley; it ends at an overlook over the crevasses and seracs on the surface of the ice. From here you can often hear the glacier cracking as it flows down the valley. To reach the trailhead we backtrack along the river. It looks narrow and fordable, but UNDER NO CIRCUMSTANCES TRY TO FORD, JUMP, SWIM, LEAP FROM ROCK TO ROCK, ETC. TO CROSS THE STREAM. USE THE BRIDGE.

Day 6—Wednesday 19 November. As we depart from Franz Josef and head north toward Hokitika, watch for landslide scars in the mountains to the east of the road. The rapid uplift of the Southern Alps coupled with this area’s high rainfall (9000 mm/yr) make for unstable slopes and frequent landslides. You may also be able to spot moraines from older, greater extensions of glaciers that reach out onto the coastal plain.

West Coast Gold- Significant quantities of gold were produced in the area from Ross north to Hokitika and Greymouth in the 19th century. Virtually all of this gold recovered from the region occurred as placer deposits. Gold typically occurs as a nearly pure metal (a "native" element) in hydrothermal veins. Because gold is both very dense (specific gravity 19.3 vs. 11.4 for Pb) and chemically inert, it persists through the weathering cycle and can be concentrated as a lag deposit in sands and gravels. Most of the gold in the Ross to Greymouth region was eroded by the vigorous west coast glaciers and deposited in glacial outwash, or outwash deposits reworked by stream or beach processes [Beanland, 1987 #3]. These alluvial deposits are called placers. Between Greymouth and Hokitika there are a series of marine terraces that were prime gold prospecting areas. The terraces consist of a seaward facing cliff with a marine beach deposit at its base. Many of these marine terrace deposits are "blacksand leads"—lag deposits of heavy minerals washed out of the material that originally made the adjacent cliff (Suggate 1978). You are familiar with blacksand leads from Stradbroke Island. Blacksand leads on the west coast of the South Island indicated to prospectors that heavy material, including gold, had been concentrated. Prospectors used a variety of techniques to find and concentrate placer gold, including one you're probably familiar with – panning. Mechanized dredges are used for commercial placer mining today; however, there are currently no active gold mines in this area. The terraces would be worth noting even if they did not contain gold. Between Hokitika and Greymouth there are successions of marine cliffs/terraces extending more than 11 km inland with elevations up to 300 m above modern sea level (Suggate 1978). These raised terraces result from a combination of tectonic uplift and glacial/interglacial and eustatic sea level fluctuations. Time, weather and equipment permitting, we'll try our hands at a little gold panning.

West Coast Jade—The term jade applies to two different hydrothermal minerals (really to two different monomineralic rocks). The most precious form of jade, sometimes called "Imperial Jade," is composed of the sodium aluminum silicate mineral called Jadeite, a single-chain silicate. The other more common form of jade is Nephrite jade, which is composed of a calcium, iron and magnesium double chain silicate, typically ferroactinolite. Jadeite is an example of a pyroxene, nephrite an amphibole. Both forms produce dense, green, translucent masses that are valued both for their beauty and, in the past, their utility. The latter property comes from the structure of the material. Both the pyroxene and the amphibole minerals occur in elongate crystals. In jades, these crystals are a few microns across and many microns long. They are intergrown in complex, interlocking patterns to produce a very tough and durable material. Most materials that we think of as tough are very hard, but also brittle. Jade is different. Jade is soft enough to be relatively easily worked, but is nearly unbreakable. Because of this, Maori jade was a prized material both for carvings and for superior stone tools. In fact, the Maori had a major collection and trade network for pounamu (jade) up and down the West Coast, across Arthur's Pass and across the Canterbury Plain to ports that took the material to settlements on the North Island. In New Zealand, nephrite is found as boulders in streams draining the Southern Alps. The location of major pounamu boulders were closely guarded secrets among Maori traders. Many of these nephrite boulders were discovered by Kiwis of European descent during the gold rush days, but in recent years supplies have dwindled and prices have risen. Hokitika remains the center of New Zealand's jade carving industry.

Stop 1: Hokitika

We will stop for lunch and some free time in Hokitika. It was a booming port during the gold rush years, but now is a little tired and struggling to maintain an economy from the few tourists that venture up the West Coast. Hokitika is greenstone central and we'll give you a couple of hours to explore the shops. If you do plan to buy jade, be a responsible consumer. A number of the merchants have been purchased by overseas interests, who sell jade imported from China, usually at a slightly lower price. You want the real New Zealand article. Ask questions of the merchants and buy local. Hokitika really needs your dollars and the current favorable exchange rate stretches your buying power.

Stop 2: Rocky Point Scenic Reserve
The road turns to the right at the intersection of several large valleys. This is the intersection of the Hope Fault with the Alpine Fault. While the Alpine Fault is a linear and singular feature south of here, from this point to the northeast is breaks into a series of strike-slip faults. Rocks exposed along the south and east sides of the road are biotite and garnet Haast Schist. The Alpine Fault lies within the river valley (why do you think this would be?) just west of the road. On the opposite side of the river are granites of the Hohonu Range (Cave 1986). Cave (1986) mapped these as mid to late Paleozoic in age, but Waight and colleagues (1997) have measured U/Pb zircon ages from these rocks of 114-109 Ma. The juxtaposition of these two very different rock types on either side of the fault speaks to the tremendous displacement along this transform plate boundary.

As we continue along the road, note where the Otira River (entering from the right) joins the Taramakau River as the road bends sharply to the right. At this point, we leave the trace of the Hope Fault, which continues eastward, becoming part of the Marlborough Fault System. The 1888 7.3 magnitude Glen Wye earthquake was produced by movement along this fault with its epicenter in Marlborough. Also watch for the landslide "chute", a concrete structure over the roadway that is designed to carry landslide debris over the roadway and dump it into the gorge below. This is part of a major engineering effort to decrease earthquake and landslide hazards along this important road.

Stop 3: Otira Viaduct Viewpoint
This engineering marvel is the NZ$25,000,000 solution to a long-standing problem on this road: avalanches. In this area, the road formerly ran along the northeast bank of the river over a blanket of avalanche deposits that are unstable and mobile. For years, the road required significant annual maintenance as the river chewed away at the base of the avalanche deposits. The bridge was completed in 1999. It consists of three piers with 134 spans. It is specifically designed to withstand a catastrophic earthquake (MM IX) and rock fall. Geological investigation done before construction revealed several facts about the rock fall. Radiocarbon dating of wood at the base of the original avalanche deposit were dated at 1900 BP. The distribution of debris also suggested that the avalanche occurred as one event, probably a major earthquake. When it fell, it dammed the river and formed a lake upstream of the debris, however, much of this material has been removed by the river. Weather permitting, you can locate the source of the avalanche material.

Also take some time to look at the blocks of rock strewn about the parking area. Notice that these are only weakly metamorphosed and still retain most of their original sedimentary textures. These are Torlesse Group rocks and virtually all of the mountains we will see from here to Christchurch are made of this stuff.

New Zealand's Cheeky Kea—At any stop from here through Arthur's Pass you may see Kea, New Zealand's endemic alpine parrot. The wild population of Kea is estimated at between one and five thousand birds and they are a protected species. Kea are curious and very assertive birds. They are attracted to things like cars and backpacks and with their strong beaks they can do considerable damage. For example, they will strip all the trim and rubber off a car! They are also attracted to shiny objects like watches, glasses and jewelry. The New Zealand Department of Conservation website claims that most Kea are good birds, and the majority of damage is caused by a few "problem birds." They have a banding program to identify and help deal with these miscreants! They also note that problems with Kea are greatly increased in areas where humans feed the birds. Please refrain from doing so! Also, many birds are accustomed to people and quite bold. While this may seem like an ideal opportunity for some up-close and personal with the wildlife—Beware! You find yourself in a wrestling match over your camera, watch or necklace with a set of sharp claws and powerful beak. My money's on the kea.

Day 7—Thursday 20 November. We'll begin the day with a short walk up to some spectacular waterfalls above the village of Arthur's Pass. This will give you another look at the high elevation, wet beech forest. Mostly it's just picturesque and a chance to get the blood moving before another big day of travel.

As we leave Arthur's Pass on the bus, watch for glacial landforms, such as U-shaped valleys, hanging valleys, moraines, etc. Also note the nature of some of the large streams—braided channels choked with sediment. This is the stuff of which the coastal plain near Christchurch is built.

Stop 1: Kura Tawhiti Conservation Area—Castle Hill

We will do a short hike here to look at some rocks that are very different from the dark colored, laminated Torlesse rocks visible in most of the hills. The rocks we see here are in a down-faulted inlier of younger Cretaceous to Tertiary rocks. As you look around, consider not only what you can see underfoot, but also the surrounding hills.

Notebook Assignment: What kind of rock is this? The outcrops here have very different "shapes" to what we have seen elsewhere. Why? This rock is younger than the Torlesse rocks. Compare the amount and character of deformation of these rocks to that in the Torlesse group. What is going on?

Given the striking nature of the landscape here, it is not surprising that it is also an important Maori cultural site associated with Maori myths and rock art. The spot was an important stopover on the greenstone trade routes to the West coast and today has protection as an important Maori cultural site. Visitors are asked to stay off the rocks in respect for the site's cultural significance.

Stop 2: Torlesse Range Pullout

The rocks exposed here are near the type section of the Torlesse Supergroup [Sugate, 1961 #11], a kilometers thick pile of interbedded greywackes (sandstones with rock fragments and a clay rich matrix) and shales that range in age from late Paleozoic through Mesozoic. Rocks like these outcrop over about a quarter of the South Island in an elongate belt along the Southern Alps. To the east they are unconformably overlain by later deposits. To the west they grade into the Haast Schist, a metamorphosed equivalent. Torlesse rocks are notoriously difficult to work with—they are of unknown age but huge thickness, contain few distinctive lithologies or marker beds, are rarely fossiliferous and are strongly deformed. In this area, Torlesse rocks are mapped as Triassic and Jurassic (Suggate 1978) in age (early to middle Mesozoic). The rock types we see here are typical of Torlesse, but elsewhere these lithologies are found interbedded with spilitic lavas—ocean floor basalts that have been modified by sodium rich fluids (like heated seawater).

Notebook Assignment: Describe the rock types you can see in this outcrop. Where would rocks like this have been deposited? What type of sedimentary environment? Compare the sediment here to that we saw on Stradbroke Island and the Precipice Sandstone at Saddlers Springs. Sketch some of the beds here—what has happened to them since they were deposited? Is there any evidence of metamorphism here? Compare them to the Alpine Schist we saw at Franz Josef.

We will continue on to Christchurch. You will have the remainder of the day free and we will give you a cash allowance for supper. As you plan your evening, please be mindful that our flight to Wellington is very early!

The North Island

Figure 8: The North Island of New Zealand showing our travel route and the location of overnight stops.

Day 8—Friday 21 November. We will fly from Christchurch to Wellington, New Zealand's capital city. We will arrive downtown early and give you a couple of hours to look around down town, grab a cuppa. We will meet at Te Papa at 10 a.m. Te Papa ("Our Place") is New Zealand's national museum of history (natural and human) and culture; it opened in 1998 to international acclaim for its innovation and approachability. Te Papa has a wonderful geology hall that outlines the nation's geologic history using vivid images and interactive displays. It also has a huge Maori collection including its own *marae* (meeting house). Natural history and native animals are highlighted as well. As you enter and leave the building, note the engineering solutions to the seismic problem. You could spend several days exploring Te Papa. Unfortunately, you will have only two hours -- be strategic in what you choose to see. We will reboard the bus at noon for the trip to Tongariro National Park.

As we leave Wellington, note the steep cliffs that seem to squeeze the highway into the bay. Once again, we are traveling on the trace of the great strike-slip fault that forms the local plate boundary. Take a moment to reflect on the seismic hazards presented by building one's capital on such an unstable piece of ground.

New Zealand's History...in Brief—Since we don't have much in the way of geological content today, it's a good time to brush up on your New Zealand history and culture. The human story in New Zealand is relatively brief. In fact, New Zealand is the last large landmass on Earth (apart from Antarctica) to be settled by humans. The Polynesian forebears of today's Maori probably arrived around 1200 CE. Some have suggested earlier dates based on inferred human impacts to the environment. However, archaeology does not place humans on the North Island until about 800 years ago. Beyond this point, the story gets murky. Did the first settlers come in one group or several, spread over years, decades or centuries? Where did they come from? Most evidence points toward several immigration events. For some of the later arrivals, oral histories are sufficiently fresh to contain details that still match with historical landmarks. For example, the *Tainui* canoe arrived in Kawhia on the west coast of the North Island sometime in the 14^{th} Century. The story goes that the two leaders, Hoturoa, the captain, and Rakataura, the high priest, knew that the group's home would be along the west coast. They searched up and down the coast until they found the spot foretold in the prophesies. When they landed the canoe, they tied it to a pohutukawa tree, which they named Tangi te Korowhiti. Although the exact tree is not marked, it is one of a small stand still growing along the shore. At the end of its voyage, the *Tinui* was dragged up the hill and buried as was traditional, with the bow and stern marked with stones. The site remains sacred to the local community.

The initial Maori settlements were in the relatively warm coastal environments where the crop plants they brought with them from Polynesia (e.g., kumara a sweet potato-like starch, gourd, yam and taro) grew well. There was also abundant big game in the form of a dozen or so species of moa, a large, flightless bird that weighed up to 240 kg. This rich food supply allowed rapid population growth and within about 100 years, the Maori had explored all of Aotearoa ("Land of the long white cloud" as New Zealand is know to the Maori). However, within about 200 years of arrival, all of the moa had been hunted to extinction. The Maori economy turned to small game hunting (birds and rats), gardening and fishing. This change required the development of detailed knowledge of the local environment and a more fixed territory. As prime farming and fishing spots became rarer, competition for them increased. This triggered the rise of Maori tribal culture and inter-tribal conflict. Although the Maori never developed metal or a written language, they had a rich, complex, highly political and military culture when Europeans arrived.

The first European contact with the Maori took place in 1642 when Dutch explorer, Abel Tasman, landed in Golden Bay on the South Island. Tasman represented the Dutch East India Company and was looking for any valuable commodity. When Tasman's ships arrived, the local Maori paddled out to meet them and offered the traditional challenge: friend or foe?[2] Blind to the meaning of the ceremony, the Dutch challenged back, blowing trumpets. When the Dutch lowered a boat to take emissaries to the Maori canoe, it was attacked and four crewmen were killed. Tasman weighed anchor and no Europeans returned for 127 years.

British and French explorers renewed contact in 1769. Although there was sporadic violence, connections and some trade happened. Whaling ships began to stop in New Zealand in the 1790s. The first permanent European settlement—a mission—was established in 1814. By the 1840s, settlements based on the flax trade dotted the coast. American whaling ships also supplied many white visitors. Between 1833 and 1839, 271 New England whaling ships called at the Bay of Islands town of Kororareka (Russell).

Europeans and Americans who stayed were linked to local Maori tribes through intermarriage, which more-or-less kept the peace. Most violence occurred between traditional Maori rivals. The most bloody of these conflicts was the Musket Wars of 1818-1836. The Ngapuhi general Hongi Hika from the North Island acquired muskets in trade, trained his warriors, and set about raiding tribes who did not have firearms. However, these tribes soon acquired guns and continued the raiding. Lasting peace was only achieved when all Maori had guns and the balance of power was reestablished.

When Europeans returned to Aotearoa in 1769, about 85,000 to 110,000 Maori probably inhabited the islands. War killed about 20,000 during the first 100 years of European occupation. Diseases also took a toll, but not to nearly the extent as in Australia or the Americas. New Zealand's remoteness acted as a natural quarantine for many infectious diseases. New crops like potatoes and new protein sources such as pigs improved the nutritional status of many Maori, allowing populations to grow. However, by the 1840s, Maori populations had dipped to about 70,000.

By the 1830s, Maori with established connections with European settlers ("pakeha" a term still used to refer to Kiwis of European descent) were benefiting significantly from the interaction and wanted more. In exchange, the Maori agreed to nominal British authority. On 6 February 1840, the British signed a treaty at Waitangi, making New Zealand a British colony. The Treaty of Waitangi has the legal force of the constitution, but is significantly more open to debate. At the heart of the disagreement between Maori and colonizers is an ambiguity between the English and Maori translations[3] of the document. The English version promised Maoris full equality as British subjects in return for the British having the exclusive right to govern. The Maori version promised that the Maoris would retain their tribal leadership and local government. This discrepancy did not present a problem in the 1840s because European settlements were small (totaling about 2000) and the Maori version of the Treaty applied outside of the small European settlements. However, as European settlements grew in population (by 1850, 22,000 Europeans lived in New Zealand, by the 1880s, they totaled 250,000) and sprawl, tensions increased.

Maori resistance to European expansion was formidable—comparable to the Sioux or Seminole in the States. One of the first clashes took place in the Wairau Valley in 1843. A posse of settlers set out to enforce the myth of British control and were routed by the Maori. In 1845, the Ngapuhi chief, Hone Heke challenged British sovereignty by cutting down the

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[2] You will get to see this challenge in person when we visit the Tamaki village south of Rotorua.

[3] By 1840, British linguists had transliterated the Maori language and a writing system had been developed.

union jack in Russell on the Bay of Plenty and then sacking the town. Heke and his allies pushed back three British punitive forces. Governor Gray claimed victory, but the skirmishes confirmed that the North Island was a European fringe around an independent Maori heartland. Armed conflict continued to flare on the until 1872. The Maori were gifted with several talented leaders and were able to score victories against better armed and more numerous British forces. Eventually they were worn down and ceded sovereignty. Things were different on the South Island. The Maori population was small and lacked strong leadership, and were subdued early in the campaign.

Meanwhile, the Pakeha economy boomed from the wool industry, gold rushes and massive overseas investment. In the 1890s, the Liberals came to power and set New Zealand on its course as an experimentally progressive society. New Zealand was the first country in the world to give women the right to vote in 1893. It also introduced old-age pensions and a system of industrial arbitration and protection for unions. This progressive streak characterizes New Zealand today. New Zealand was one of the first signatories of the Kyoto Protocol in response to global carbon emissions, and has led the world in implementing emissions reductions under the treaty. New Zealand was also one of the first nations to declare itself a "nuclear free zone" in protest for Cold War arms proliferation, a decision that cost the nation dearly in trade with the United States. New Zealand has also led to world in social acceptance of and legal protection for gay, lesbian, bisexual and transgendered people.

But it's not that everything is roses. The Maori, a conquered people in the end, still struggle for land rights, economic opportunity and social equality. In the late 20th Century, New Zealand struggled to slim and reform its bloated welfare state to reflect the modern need for a leaner and quicker economy and government. It has struggled with more immigration from Asia and the social conflict that results. And as the economy has diversified to include new products and—importantly—tourism, Kiwis have struggled to maintain the pristine quality of their environment, which is so dear to them. At the same time, New Zealand has seen its literature, film and music scenes blossom, a positive sign for a country in transition.

Despite the emergence of a distinct identity that blends Pakeha and Maori influences (all official documents are written in both languages and school children study both English and Maori language), New Zealand remains a Dominion within the British Empire. In 1901, New Zealand refused to ratify the Australian Constitution and so rejected membership in the Australian Commonwealth. As a consequence of Dominion status, New Zealand technically does not control its foreign or military affairs. However, the Crown has been content to allow the far-away nation considerable control over its internal affairs, and has, in some cases (e.g., carbon emissions controls), followed the Kiwi example.

We will arrive at Discovery Lodge in National Park for supper.

Days 9-11—22-24 November. We will spend three full days in the Tongariro region with the hope of getting in two long day hikes: the Tongariro Crossing and the Ruapehu crater climb. Both depend on good weather and favorable geological conditions (the Ruapehu volcano was recently upgraded from "typical background surface activity" to "signs of unrest". You can watch for further bulletins on the Program web site[4], where we have posted an RSS feed linked to New Zealand's GeoNet.). As good weather can be in short supply during the spring, the extra day allows us greater flexibility in choosing our schedule and, if all goes well, will allow us a full day to tour the spectacular outcrops surrounding the Tongariro

[4] http://academic.hws.edu/Kendrick/OZ2008

Volcanic Center and examine some of the hazards that arise when humans live in proximity to active volcanoes.

Tongariro Volcanic Center—Welcome to the heart of Mordor. This andesitic center is the youngest on the North Island. It consists of the volcanoes Tongariro (1967 m), Ngauruhoe (2287 m), and Ruapehu (2797 m, the highest point on the North Island. If the weather is fine, you can see the Tasman Sea to the west and the Pacific to the east from the crater rim of Ruapehu. It truly is a compact country!). Ngauruhoe is a satellite vent of Tongariro, but it has the best developed volcanic cone shape and is easy to pick out. If you've seen Peter Jackson's film adaptation of "Lord of the Rings", you might recognize it as the basis of Mt. Doom. Tongariro and Ruapehu are larger volcanic features, but because of their longer and more complex histories, they do not retain the typical stratocone volcano shape. Both have been modified by lava flows, side eruptions, lahars, landslides, small vent collapse and rock avalanches.

The vent complexes (the mountains themselves) are surrounded by gently sloping "ring plains". Eruptions seem to have begun in this area roughly a million years ago and continue to the present. Ngauruhoe last erupted in 1975 but has active fumaroles along its flanks. Ruapehu last erupted in 1995-1996.

Ruapehu Volcano—Ruapehu is located at the southern end of the Taupo Volcanic Zone, a thermally expanding segment of the Earth's crust and the source of spectacularly explosive eruptions over the last 2 million years. Because the crust is heating up here, it is expanding, creating tension, extension, normal faulting and subsidence in the central axis of the Taupo Volcanic Zone. Prominent active faults have developed to the east and west of Ruapehu volcano, which are downthrown towards the mountain. These faults mark the boundary of the Taupo Volcanic Zone in this region, which terminates 20 km south of Ruapehu's summit [Neal, 2006 #12].

Accumulations of andesite lava flows interbedded with fragmental rubble radiate from the summit region forming a stratovolcano that rises 2000m from the surrounding lowlands. As stratovolcanoes build up they become steep and have a propensity to collapse, spreading outwards onto the surrounding lowlands and forming a roughly circular apron of fragmented rocks (volcaniclastics) termed the "ring plain". Ring plain deposits are mainly derived from debris avalanches and lahars, but may also include some river (fluvial) and glacial deposits. Mantling the lowlands are various thicknesses of volcanic ash forming the parent material of most of the soils in the region. Due to the dominantly westerly wind direction, ash is always considerably thicker to the east than to the west. A crater lake dominates the summit area. When full to overflowing, the lake contains 8-10 million m^3 of warm to hot acid waters. Overflow of the crater lake can generate huge lahars or volcanic mud flows. Lahars have been responsible for most of the loss of life on the New Zealand volcanoes (Neal et al. 2006).

The oldest lava sequences preserved on Ruapehu are exposed on the northern flank and seem to date from about 300,000 years ago. The distinct stratocone was built between about 250,000 and 130,000 years ago. During this period, voluminous lahars were also generated. These inundated the nearby hill country of uplifted marine siltstones, sandstones and limestones, creating the extensive ring plain, especially to the north and to the west of the Whakapapa catchment. The resultant deposits total more than 12 km^3 in volume. A second cone-building phase occurred between 60,000 and 15,000 years ago, during which time lavas of variable composition were extruded from several vents between Tahurangi and the northern Summit Plateau. Lahars were also generated during this time, leading to further deposition on the western and southwestern ring plain. Considerable volcanic ash also

accumulated downwind of the volcano. At about 30,000 years ago, basaltic magma erupted scoria and surge deposits from a satellite vent on the northern outskirts of Ohakune. South of Ohakune, the magma encountered groundwater, which flashed to steam resulting in two additional explosion craters that form Ohakune Lakes. Around 25,000 years ago basaltic andesite erupted from the southwest flank of Ruapehu, spreading lavas across 4 km^2. Later similar flows were generated from the southern flank to form the Rangataua lava flows around 18,000 years ago. During this period the climate was colder than at present and most river beds were choked with sediment (aggraded) as further lahars spread laterally both to the west and to the east. Lahar deposits total in excess of 3 km^3 volume. During this time, more explosive magmas erupted, showering the eastern ring plain with successive thick pumice layers. The last of these events occurred about 10,000 years ago. The climax of these events was a major structural collapse of the northwest flank that produced a debris avalanche that swept down the Whakapapa catchment to beyond State Highway 47, covering 23 km^2. Small-scale ash eruptions accompanied by lahars occurred between 9,500 and 4,500 years ago. Sometime between 4,500 and 3,500 years ago, instability of the upper cone led to 34 million m^3 debris avalanche that swept to the east across the Rangipo Desert. It covered 20 km^2 and destroyed a widespread beech forest on the southeastern ring plain at the time.
In historical time the earliest report of eruptive activity at Ruapehu was in 1861 when a lahar was sighted in the Whangaehu River (Neal et al. 2006). Mr Henry Sergeant described the lahar in the vicinity of Wyley's Bridge:

> "In the mid-summer of 1860-61…I was standing on the bank (of the Whangaehu River) …when I suddenly saw coming around a corner in the distance a huge wave of water and tumbling logs. They filled the whole trough of the stream…As it passed us it appeared to be covered with what we first thought to be pumice but the intense cold which soon made us shiver and turn blue caused us to discover that …(this) was no less than frozen snow. Mixed with this was a mass of logs and debris. Very soon a bridge passed us stuck in the roots of a giant tree and a few minutes later about a dozen canoes came down".
>
> (Neal et al. 2006)

A major eruption was recorded in 1895 and another in March 1945, which spread ash from Wellington to the Bay of Plenty. Ash eruptions peaked in August and September, and by December 1945 the activity subsided leading to a deep, vertically walled crater which slowly refilled with water. More lahars occurred in 1968, 1969, and 1975 as water levels in the crater lake rose and fell. Beginning in early 1995, small steam eruptions were forerunners of two moderate phreatomagmatic (steam or wet magma) explosions on 18 and 21 September. A spectacular though small phreatomagmatic eruption spread ash, bombs and water across the ski fields (we'll hike up these weather permitting) in the late afternoon of 23 September. Volcanic mud and tephra continued to erupt from the crater lake producing a nearly continuous stream of lahars. On 11 October, the lake was completely drained and "dry" eruptions began, spreading ash northwestwards to Gisborne. Activity then subsided after several weeks and in early November 1995 a new lake began to form in the crater. Ruapehu's most recent major ash eruption began in the early morning of 17 June 1996, when a strong southerly wind carried the ash in a narrow plume northwards across Rotorua. Periodic ash eruptions continued through August (Neal et al. 2006).

Volcanic Hazards—A variety of volcanic hazards are associated with Ruapehu. In general, these could apply to almost any volcano of this type.

Lava domes and flows. Lava domes have been extruded at Ruapehu once and possibly twice in historical times (in 1945 and possibly 1861), but little remains of these today. Lava domes are bulbous masses of viscous lava slowly extruded from a vent. The radius of a lava dome is typically between a few hundred metres and 1-3 kilometres. Extrusion of a lava dome in the currently active summit vent poses few direct problems, all of which can be managed with use of an "exclusion zone" around the summit. The lava flows at Ruapehu have occurred from summit vents during the Holocene. Lavas are channeled down existing valleys at rates that seldom threaten human life. Hazard zones in which all structures would be destroyed are elongate and would extend typically several kilometres from the active vent (Fig. 9).

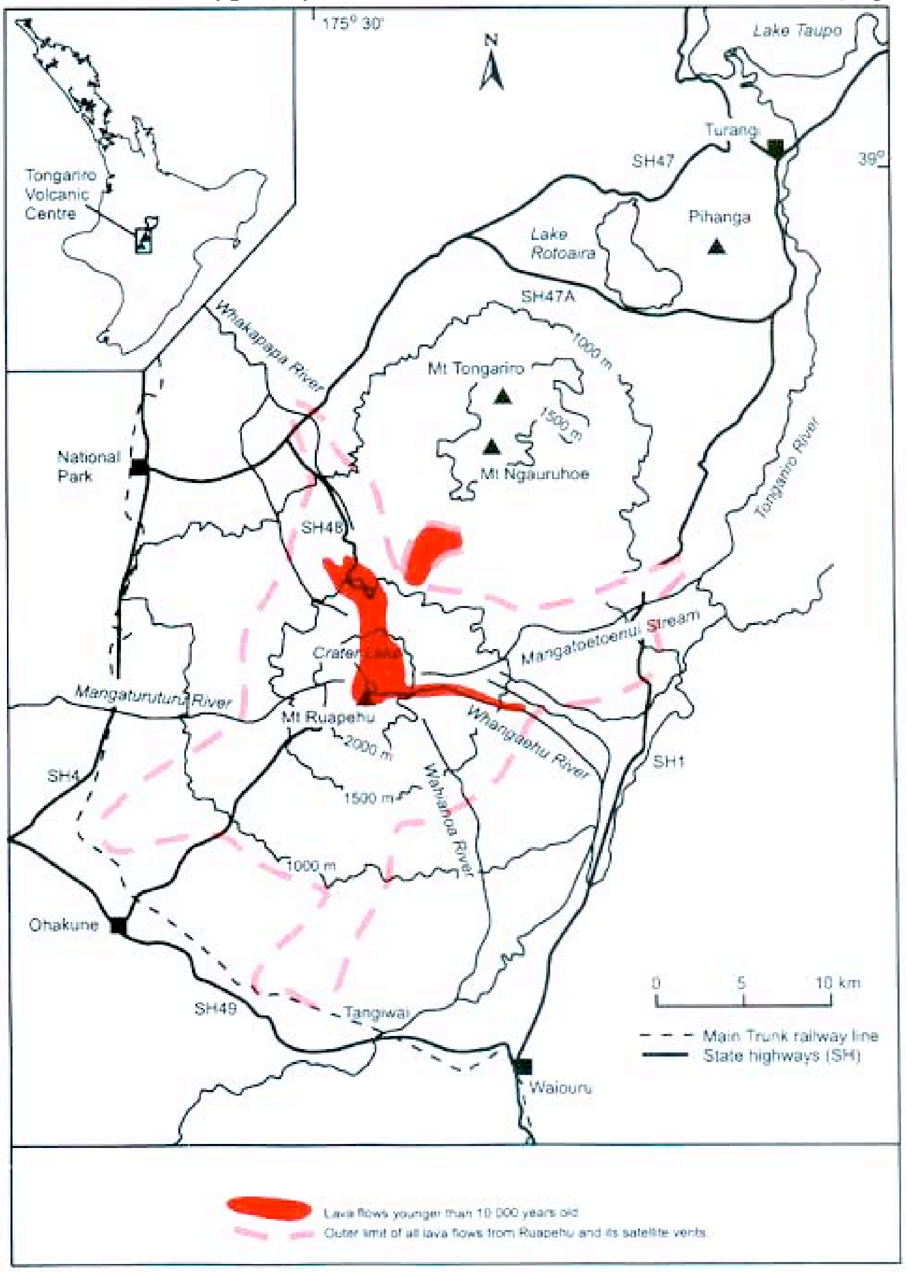


Figure 9: The distribution of lava flows at Ruapehu both prior to and since 10,000 years ago.

Pyroclastic flows. Pyroclastic flows appear to be uncommon at Ruapehu. Pyroclastic flows are dense, rapidly expanding clouds of hot gases that transport particles in fluidized masses down valleys and across surfaces of low gradient until the flows lose mobility by dissipation of the gases. If the speed, volume and momentum are sufficient, pyroclastic flows may travel uphill or across areas of irregular relief, but usually they tend to be channeled into river courses and into depressions. Pyroclastic flows travel at speeds of up to 200 km/hour.

Temperatures of up to 828°C have been measured in pumice flow deposits erupted from Mt St. Helens in October 1980. The principal hazards of pyroclastic flows are the dangers due to their extreme heat and high speed. They can be highly destructive and unpredictable and may form with little warning (Neal et al. 2006).

Volcanic debris avalanches. In some large andesite stratovolcanoes the interlayered strong and weak rock units typical of stratocones lead to planes of weakness. Infrequently, failure may occur along these weaknesses triggering extremely large, high velocity landslides called volcanic debris avalanches. The classic modern example is the failure of the north flank of Mt St. Helens on 18 May 1980 when approximately 2.5 km^3 of the cone avalanched 27 km downstream as the result of a minor earthquake. Volcanic debris avalanches appear to be triggered most frequently by small earthquakes associated with magma intrusion, but some are triggered by large magnitude tectonic earthquakes, or by exceptionally heavy rains saturating the volcanic pile. Ruapehu could be vulnerable to collapse if its interior has been altered by acid fluids percolating from vapor-rich geothermal systems; however, that's currently an unknown. In any event, all physical structures in the path of a debris avalanche will be destroyed or buried. Sometimes volcanic debris avalanches may block drainage systems to form permanent or temporary lakes that may break out to form lahars. At Ruapehu, two volcanic debris avalanches have occurred in the last 10,000 years (Fig. 10, Neal et al. 2006).

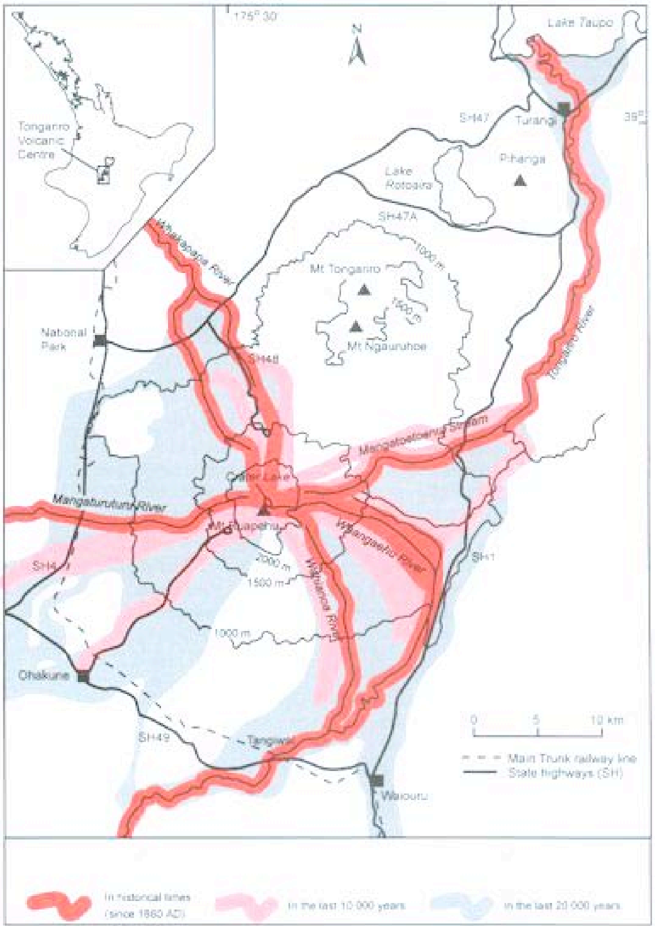


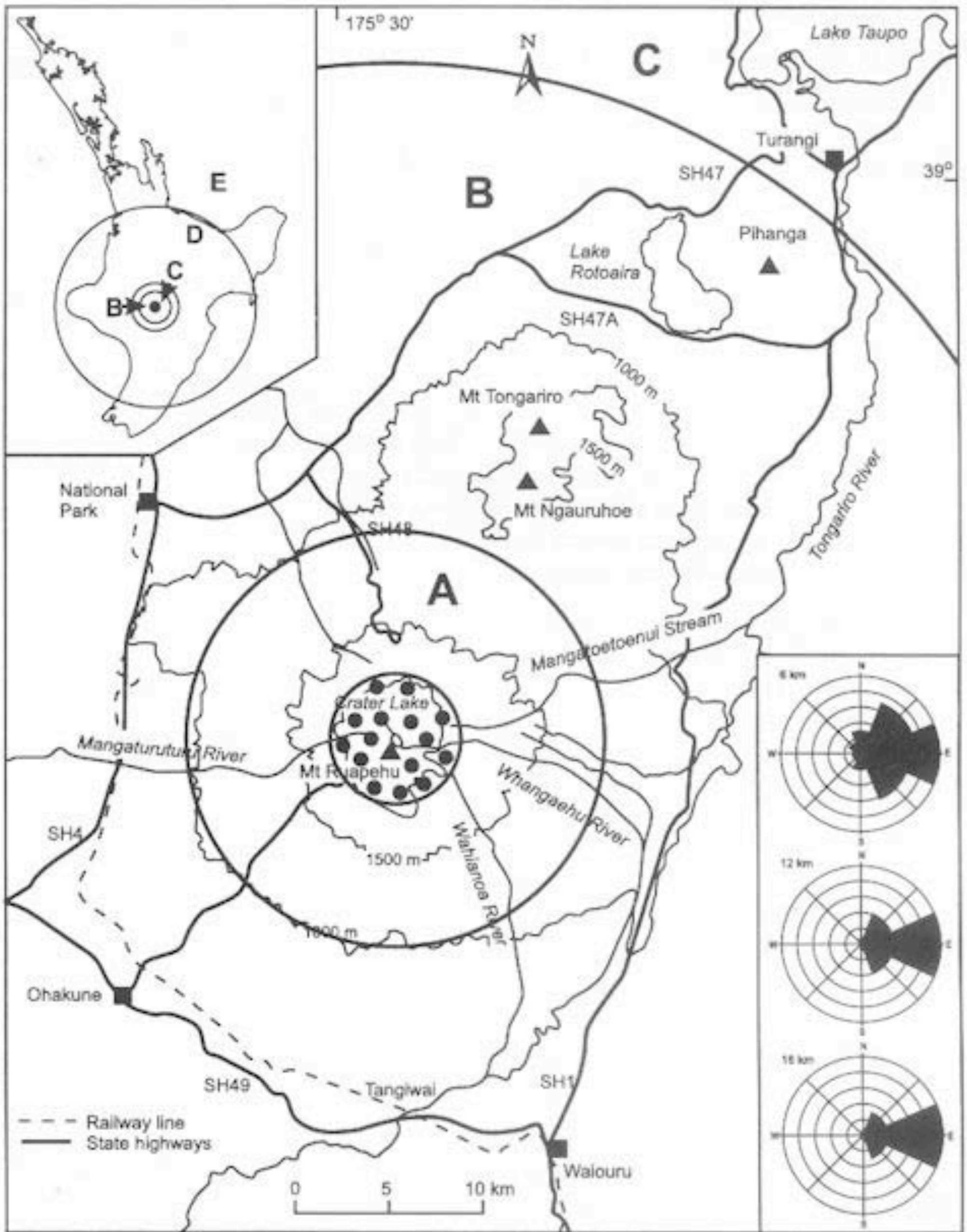
Figure 10: The distribution of volcanic debris avalanches, lahars and associated floods at Ruapehu in historical times, and over the last 10,000 years and 20,000 years (Neal et al. 2006).

Lahars and volcanic floods. As discussed above, a lahar is a rapidly flowing mixture of rock debris, sand, silt and water (other than normal streamflow) originating from a volcano. Most of the destruction and loss of life associated with Ruapehu is caused by lahars (Fig. 10). Lahars resemble wet concrete as they flow. They are guided along drainage channels into deep gorges or even along shallowly incised stream channels at low gradients. The lahar's velocity depends on the density of the flow, the gradient of the ground surface and the volume and depth of flow. If large enough volumes of material are incorporated on initiation and there is sufficient elevation drop, a lahar may travel hundreds of kilometres. Speeds of between 10 and 90 km/hour were recorded for lahars during the 1995 eruptions at Ruapehu.

Lahars can be generated in a variety of ways. The primary elements are water and loose volcanic debris. Large volumes of water are often stored in crater lakes (e.g. Crater Lake on Ruapehu) and when the rim of a crater lake collapses or when eruptions occur through a lake, these waters may be released. Pyroclastic flows have generated lahars as they mix with river or lake waters, or glacial snow that is flash-melted by the eruption. Heavy rains on the flanks of a volcano may saturate loose materials that become unstable, fail and then flow as a lahar.

Tephra. Tephra is all material that is blown out of the vent and through the air. It includes: ash (less than 2 mm diameter = sand or smaller sized particles), lapilli (2-64 mm diameter) and blocks or bombs (greater than 64 mm in diameter). Tephra can be dispersed widely through the atmosphere, with some material being launched into the stratosphere and being carried for tremendous distances. Tephra poses two types of hazards (1) problems created by the physical presence of tephra (e.g., building collapse, machine fouling, and asphyxiation), and (2) potentially harmful substances adhering to tephra particles that can poison or pollute water supplies and animal foodstuffs. The effects are very much dependent on particle size, tephra thickness and distribution. For humans and animals, exposure to fine ash can lead to breathing problems despite the natural filtering mechanisms operating in the nasal passages, because particles smaller than 0.01 mm can penetrate to the air exchange regions of the lungs. If free silica particles are abundant in the ash, the danger of silicosis is also increased. Incidence of diseases such as "industrial" bronchitis, acute and chronic obstructive pulmonary disease (COPD) or emphysema and asthma are likely to increase in areas where more than 10 mm of ash falls, and more especially when greater than 50 mm of ash deposition is experienced. Besides the direct effects of ash inhalation, there is also the secondary problem of ash covering vegetation and affecting the palatability of livestock feed or even burying it completely. As such, livestock and the natural fauna are affected by tephra could experience respiratory diseases, excessive tooth wear, and starvation. In the 1995 eruptions of Ruapehu, some fluorine toxicity was also experienced with pregnant sheep grazing ash-coated pastures. Based on the previous eruptive history of Ruapehu, a tephra hazard-zonation map has been compiled with expected tephra thicknesses for (1) a small magnitude eruption (e.g. 1995) and (2) a large magnitude eruption, typical or larger eruptions that occurred at Ruapehu between 10,000 to 20,000 years ago (Fig. 11).

Volcanic gasses and acid rain. Volcanic gases consist predominantly of steam (H_2O), followed in abundance by carbon dioxide (CO_2) and compounds of chlorine and sulfur. Minor amounts of carbon monoxide, fluorine and other compounds are also released. Concentrations of gases will dilute rapidly away from a volcano and pose little threat to people more than a few kilometres from the active vent. Eruptions at Ruapehu volcano are accompanied by very high fluxes of acidic gas, especially sulfur dioxide (SO_2). This is because large quantities of these gases are dissolved in Crater Lake during non-eruption times and "stored" in the lake water until an eruption occurs. During the 1995-96 eruption the flux of SO_2 reached values in excess of 15,000 tons/day, exceptionally high by world standards. Consequently, a significant gas hazard is present in Crater Lake basin at most times.



The probability of tephra fall in each zone is proportional to the probability of wind directions shown in the wind rose diagrams from Auckland Airport at altitudes of 6, 12 and 16 km. Expected thicknesses of tephra (in mm) in each zone for (1) small-magnitude eruptions and, (2) large-magnitude eruptions are as follows:

Zone	A	B	C	D	E
(1)	>40	10-40	5-10	1-5	<1
(2)	>300	80-300	30-80	10-30	<10

Ballistics hazard zone where there is greatest risk from blocks and bombs.

Figure 11: Tephra hazard zones for Ruapehu based on data from past eruptions of various sizes (Neal et al. 2006).

During an eruption a portion of the ejected SO_2, HCl and HF dissolves in water droplets in the eruption plume to form aerosols (droplets and tiny particles) that rain out over the landscape with the ash. This mixture often creates acid rain and an atmospheric haze known as volcanic smog. These very acidic water droplets can irritate humans' and animals' eyes and impair respiration, cause extensive damage to crops, corrode metals, and foul water supplies (Neal et al. 2006).

Ruapehu Crater Climb—This is a five to seven hour walk, much of it across snow fields of the Mt. Ruapehu Ski Area (Fig. 12). Our goal is to reach the summit crater of Mt. Ruapehu. The crater contains an active, hydrothermal lake floored by molten sulfur! Outbursts from this lake have produced destructive lahars throughout the volcano's history. The lake is closely monitored as a guide to Ruapehu eruptive activity. We will not descend into the crater -- as Gollum would say, "Not nice! Not nice!" The water temperature is between 22-25°C, which sounds pleasant until you remember that the pH is quite low and air-displacing gasses like CO_2 and SO_2 are constantly bubbling from its surface. If the weather and the mountain itself allow us to undertake this hike, we will do so under the supervision of a local guide.

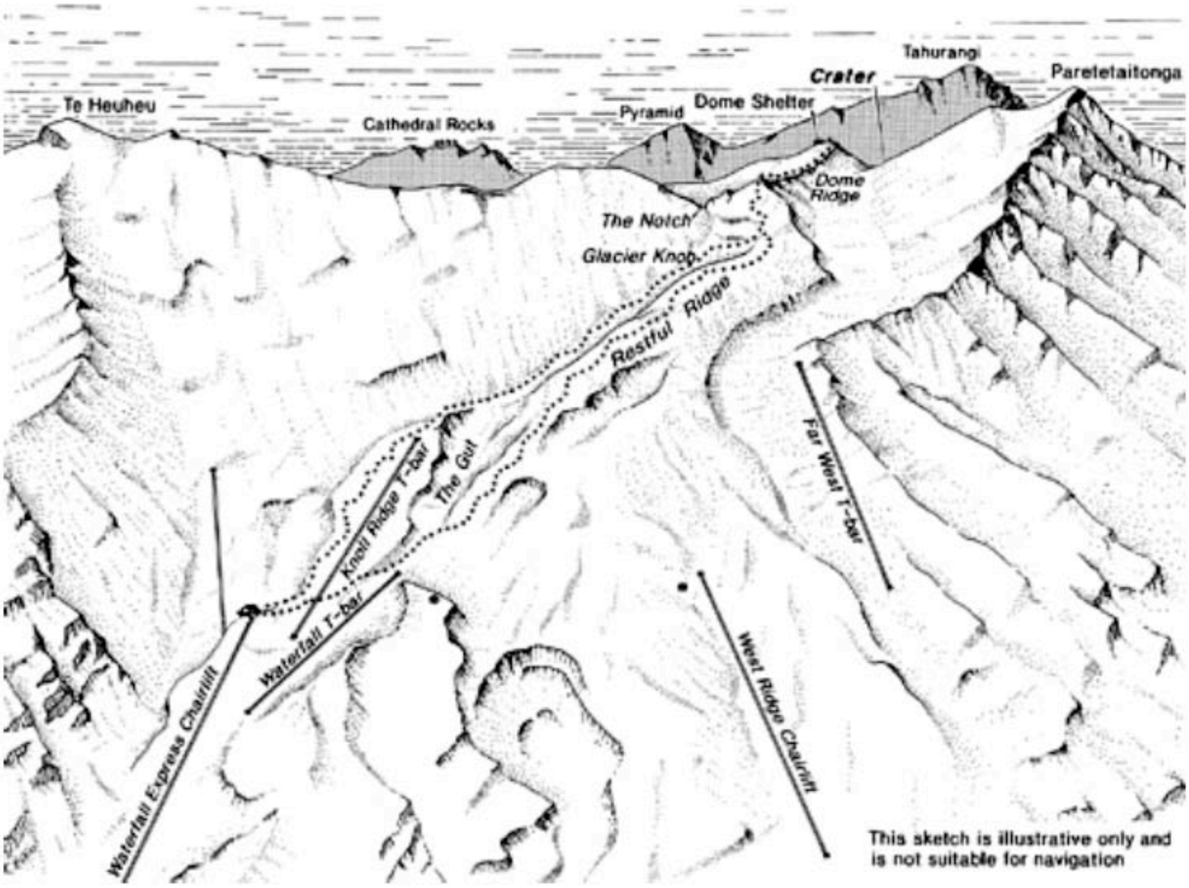


Figure 12: Ruapehu Crater Climb. Source: www.doc.gov.nz.

CAUTION: This is an exhilarating climb, but we will be moving through an area with obvious and not-so-obvious hazards of which you must be mindful and for which you must be prepared. First of all, be prepared as the weather can change quickly. We will not undertake the climb unless the weather looks good, but conditions can change rapidly and without warning. You should carry a warm hat, mittens, warm layers and a wind/waterproof shell. I also recommend an extra pair of socks. Second, carry and *drink* at least 2 L of water throughout the day. Since it's cold, you don't realize that you are perspiring and becoming dehydrated, or you may feel shy about the possibility of urinating in an open snowfield. Get over it! In 2003, one group of Ruapehu Crater Climbers didn't drink enough and became violently mountain sick (vomiting and headache comparable to the worst pub crawl of your life—no fun). Third, protect yourself from the sun. The 2005 group returned from the climb with some severe sun burns—especially to areas you would not expect. High altitude and UV reflected off the snow pack led to sunburns on lips, the bottoms of noses, chins, etc. The most painful burns were to lips. Several folks woke up the next morning feeling like we had spent the night in a lip lock with a hot iron. Recovery took about ten days. Be forewarned! Hats and sunglasses are an absolute must and even with that you will need to periodically reapply sunscreen and some type of lip protection.

Tongariro Crossing "Best Day Hike in NZ"—This is a 17 km, 6-8 hour hike that starts on the south side of the Tongariro complex, threads its way between the Ngauruhoe and Red Crater vents and then and down the north side. In addition to spectacular scenery, watch for the features below on your walk. See Figure 13 for details of the route. Note that several hundred people will make this walk on a good weather day. Some things to look for on your hike:

Mt. Taranaki (aka Mt. Egmont). If it is a clear day, you may be able to look west as you ascend toward South Crater and see this snow-covered stratocone volcano in the distance. The summit of Taranaki is about 120 km away. We will not visit this volcano, but if you have some extra time in New Zealand and enjoy hiking in rugged country, Taranaki is well worth a visit.

Mt. Ngauruhoe. You will cross the north flank of this cinder cone and it will dominate much of the early portion of your hike. Look for lava flows that have moved down its flanks. This is Mount Doom. Watch out for orcs!

Red Crater. This vent erupted explosively in 1855 and 1926 and is probably the source for some of the most recent lava flows on Tongariro. The crater is at the top of a scoria cone intruded by dikes. In one of these, molten material in the center of the dike receded, leaving frozen dike margins and a central void—look for it as your walk by Red Crater.

North Crater. This flat-topped cone, capped by a 1100 m wide crater, is filled with a solidified lava lake. A 300 m wide explosion pit is present on the northwest margin with ejected blocks up to 9 m across. We won't take the detour to get here, but you'll be able to see it from Red Crater.

Emerald Lakes. Three water-filled explosion craters with blue-green waters. Dissolved minerals from adjacent thermal springs give the water its intense color.

Blue Lake. A 400 m diameter circular, lake-filled crater. Adjacent slopes are mantled with a coarse- grained, partially welded volcanic breccia. (The clasts were still hot enough to "stick" to each other and deform as they landed.) This deposit is believed to represent fallout from a fountaining vent of magma. Blue Lake is sacred to the Maori people. Do not enter the water.

Descent from Blue Lake. Look for views of Lake Taupo along the horizon to the north. Recall that Lake Taupo occupies a set of overlapping collapse calderas from volcanoes that dwarf the combined volcanic production of Ruapehu, Ngauruhoe and Tongariro by several orders of magnitude.

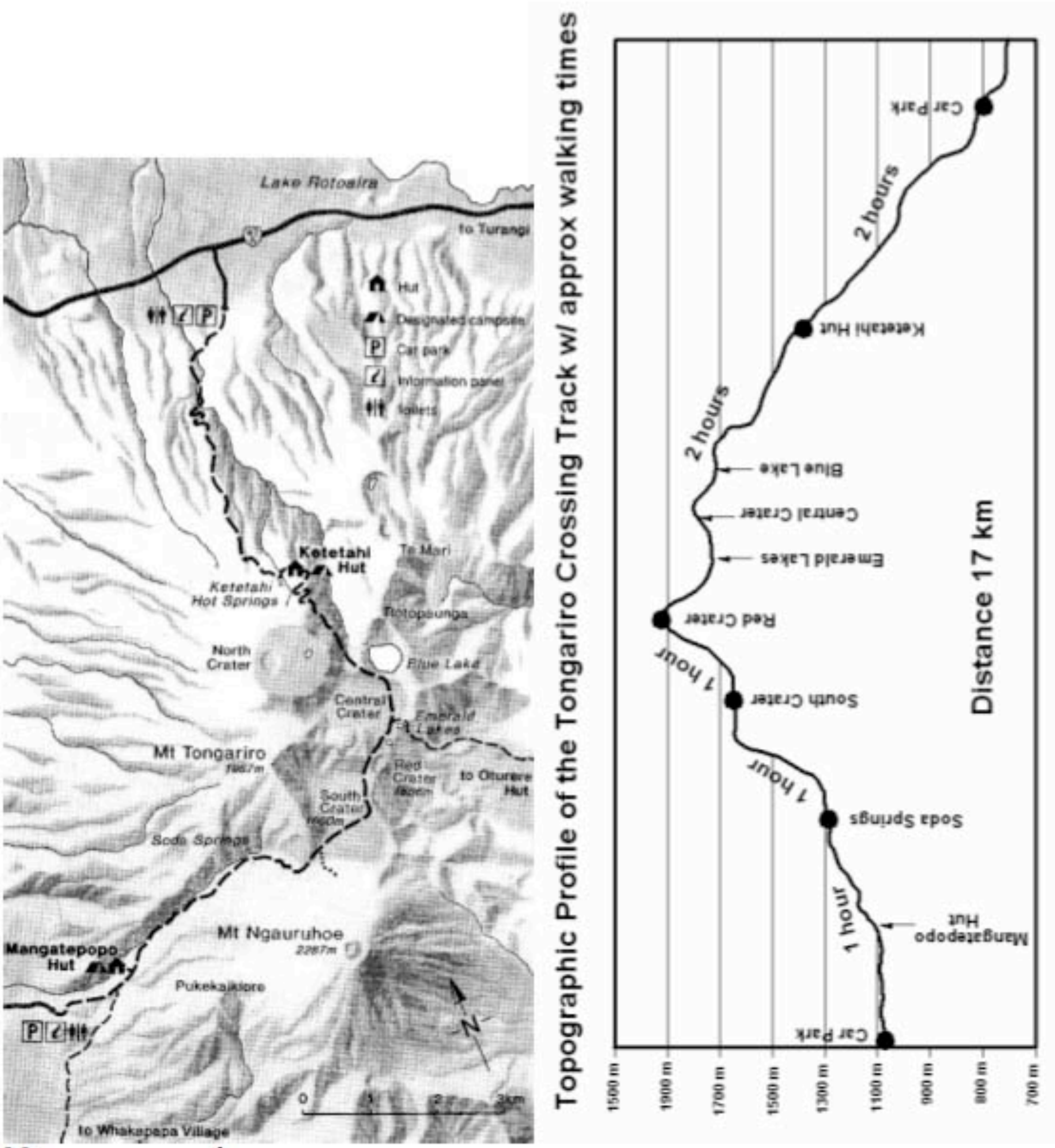


Figure 13: Map and topographic profile for the Tongariro Crossing.

CAUTION: This walk is similar in distance to the crater rim walk we did at Lamington National Park; however, the environment is much more harsh and unpredictable. You must be prepared. We will not undertake the Crossing unless the weather looks good, but conditions can change rapidly and without warning. You should carry a warm hat, mittens, warm layers and a wind/waterproof shell and pants if you have them. I also recommend an extra pair of socks. If your hiking boots are giving you trouble, invest in some moleskin before we arrive in New Zealand or bum some off of the Professors. Carry and *drink* at least 2 L of water throughout the day. You will be doing some hard work, particularly between Soda Springs and South Crater (About 1 hour into the hike, see Fig. 13) and may not realize you are dehydrated. If you haven't had to stop to use the bushes before lunch, you are probably not drinking enough. Wear a hat, sunscreen and lip protection. You are at elevation and the sun is more intense, even on an overcast day. Carry a flashlight. Hike with a buddy and stay more or less together with the group. Not everyone has the same level of fitness or stamina. We will try to divide the hiking parties into groups of similar ability, but there is always variation. This can be frustrating if you are a strong hiker and want to rock on ahead. Slow down a little, take it easy, enjoy the scenery and stay within visual contact of the slowest members of the group. This is about safety. If someone has a fall, becomes ill or has other troubles, we need to be there to help. Stay on the trail. The trail is safe and well-maintained. The area around it is not. Slopes may be unstable, and fumaroles and boiling-hot hydrothermal vents lurk just below the surface. Look with your eyes, not your feet.

Tongariro Circumnavigation—If all goes well with our hikes, the last day in National Park will be spent driving around the volcanic complex.

Notebook Assignment: Describe the vegetation around Discovery Lodge (west side of Tongariro) and on the eastern side. How are they different? What might explain this difference? What does that tell you about the weather patterns in the North Island?

Stop 1: Tangiwai Rail Disaster Site
A small roadside park and displays mark the site of the 1953 Tangiwai Rail Disaster. On Christmas eve, an ice and volcanic debris barrier built across the outlet of Ruapehu's Crater Lake collapsed into an ice cave above the Whangaehu River. About 1,650,000 m^3 of water flooded out of the lake, entraining boulders and sand across the Whangaehu fan to form a substantial lahar. About 42 km downstream, the lahar was reaching its peak discharge at Tangiwai (810 m^3/second) just as the Wellington-Auckland passenger train was crossing the rail bridge. The bridge's piers were unable to sustain the force of the debris-laden water and the weight of the train, causing the engine to plunge into the far bank and taking six of the passenger carriages into the raging torrent. One hundred fifty-one lives were lost in New Zealand's worst rail disaster. As a result a lahar detection gauge was built 15 km upstream to warn of any future lahar events that had the potential to damage the bridge.

Notebook Assignment: Sketch the landscape and make notes on the lahar deposits you can observe. Also, note and describe the "ring plain" deposits that you can see. Describe the lahar detection system in your notebook.

Stops 2+: Time permitting, we will stop at several road-cut outcrops to look at the sequence of volcanic material preserved in cross section.

Notebook Assignment: Make a regional sketch map of the Tongariro Volcanic Complex in your notebook. At each stop, note the approximate location on your regional map. If you're really clever, you'll include the location of Stop 1 as well! At each roadside outcrop, do the following: 1) Stand back and study the outcrop from the other side of the road. Make a sketch that describes the different rock units you see and their relationship to one another. Be sure to include a scale. 2) Cross the road and describe each of the rock units you noted *in detail*. Note color, composition (if you can work it out), rock type, fragment size (if it is tephra), layers (measure their thickness), banding, variation in fragment size, any distinctive features...anything you can see. When we return to Discovery Lodge, you will be drawing up your stratigraphic columns and trying to link together deposits from different locations around the region. This will be very difficult unless you have observations in sufficient detail to recognize the same deposits at different locations, so take your time and look closely.

Day 12—Tuesday 25 November. We will leave Tongariro behind and travel north into the Taupo Volcanic Zone and on toward Rotorua.

Lake Taupo lies in the collapsed calderas of several enormous volcanoes that blew themselves up in a series of massive eruptions, the last of which occurred in 186 CE [Wilson, 1980 #14]. Material from the Taupo eruptions are rhyolitic and spread over a large part of the North Island. They include, pumice, ash and a non-welded ignimbrite (pyroclastic deposits). Estimates suggest that the eruption launched more than 60 km^3 of material more than 50 km into the sky. Some geologists estimate that the Taupo eruption of 186 CE was the most violent eruption of its kind ever studied (Wilson et al. 1980). Ash from the eruption spread worldwide producing strange skies as far away as China and Europe. An article by Wilson and colleagues (1980) describing a novel way of dating this eruption appears at the end of the guidebook.

Stop 1: Five Mile Bay Recreation Area

From this stop we can look across Lake Taupo to Western Bay, site of some of the most recent volcanic activity in the area. Looks peaceful doesn't it? We want to look at three things here. First, the sand along the beach. Grab a handful and look carefully, definitely use a hand lens if you have one. The second thing to look at here are the deposits that make up the lake shore terraces to the east of the current shore line. Finally, notice the large boulders scattered along the shore. Notice that they are all about the same distance from the shore.

Notebook Assignment: Describe the sand on the beach in detail, paying particular attention to its composition. Compare this sand with other sand you've described in your notebook from other places we have visited. Next, describe the terrace deposits. Finally, have a close look at the large boulders. After you have made some good observations, suggest how the two sets of observations are related.

Some have suggested that the shoreline boulders actually floated into place. Although they seem too dense now, when hot and full of gas, some argue, they might have floated to the strand line, cooled and been deposited.

Stop 2: Taupo

We'll stop briefly to have a look at this touristy town. The guidebooks say that Taupo "rivals Rotorua as the North Island's capital of adrenalinised action." It is a big tourist spot, both for Kiwis and foreign visitors. It is also New Zealand's lake trout capital.

Stop 3: Wairaikei Geothermal Power Plant viewing area

Wairaikei was the first geothermal power station developed in New Zealand. Exploratory drilling began in 1950 and power generation started in 1958. The station produces about 150 MW of electricity. Power is derived from hot water extracted from wells that penetrate an impermeable cap of sedimentary rocks into hot, fractured volcanic rocks below. The wells produce water at about 260°C, sufficiently hot to flash to steam at surface pressures. The steam drives turbines that produce electricity.

In a world worried about burning fossil fuels for energy, geothermal seems like a good alternative for those places, like New Zealand, lucky enough to have high heat flow near the surface. However, geothermal energy is not entirely benign. Removing large amounts of water from the underground aquifer can cause the landscape to subside. This is a significant problem if your home—or town—happens to be built over the geothermal field. The water itself can also be problematic. Hydrothermal water may be acidic, contain lots of crazy (and sometimes toxic) minerals, and is, well, hot. Thus, disposing of the water once the steam has done its work and condensed can be a big problem. All those minerals also tend to clog the equipment (pipes and turbines) requiring substantial ongoing infrastructural maintenance. What do you think? A better alternative? What about if it was in your back yard?

Stop 4: Waimangu Geothermal Field
In 1886, Mount Tarawera south of Rorotua erupted in a colossal steam and ash eruption destroying the surrounding area. The explosion split Mount Tarawera in two, blasted out Lake Rotomahana, destroyed a world-famous Pink and White Terraces, a massive stair-step deposit of hydrothermal sinter silica. An estimated 120 people were killed in the eruption, most of whom were local Maori. The Maori village of Te Wairoa, buried by the ash from the eruption, has been excavated and restored as a tourist site. (If for some reason our plans are otherwise scuttled, we may visit this site.) Within a few years, an active system of hot springs developed in the gigantic crack left behind. Steam eruptions continued from 1900 to 1904 and again in 1917.

Walk quickly or take the shuttle down to the bottom of the gorge and walk up, taking your time to make observations in your notebook. Some suggestions to guide your observations:

• Describe Inferno Crater and Echo Crater. How are they inter-related? Signage will help you here.

• How hot is the water and is it the same temperature everywhere?

• Where is sinter forming? Does there seem to be any relationship between this and the temperature of the water?

• Locate and describe the buried paleosol. How do you know it's a soil? What does it tell you about the history of this area?

• Waimangu is a very important location for botany. What are some of the heat-tolerant plants that you can see here? What are some of the rare and endangered plants found here? The visitor's center will help here.

• Find a spot somewhere and sit quietly to contemplate this place. Consider the violence with which it is formed and how it feels today. Jot down a few thoughts (haiku optional) that reflect on this contrast.

Note that this list of things to look at and document is a minimal list. Full marks on today's notebook will include some of your own, original observations.

Day 13—Wednesday 26 November. We will release the questions for the final exam today. The exam will follow the same format as the midterm and take place at 4 p.m. on Friday 28 November.

Stop 1: Wai-o-tapu Thermal Wonderland

This is probably the best-known and most developed geothermal field in New Zealand. It lies at the edge of the Rotorua Caldera (like Lake Taupo, Lake Rotorua lies in a collapsed volcanic caldera). Among the features of Wai-o-tapu are the collapsed craters, steaming ground, acid-sulfate and alkali-chloride pools with shocking colors, fumaroles, geysers, hydrothermal eruption craters, and boiling mud lakes.

Acid-sulfate pools are opaque yellow-green, the color produced by suspended sulfur. These pools generally have a pH < 3, but they are relatively cool. Water comes from surface runoff that has interacted with altered rock and SO_2 gas emerging from the magma below. In contrast, alkali-chloride pools are filled with water that has come from deep hydrothermal aquifers. This water may be 22°C or warmer and are saturated in silica. They precipitate a lovely white sinter.

The Champagne Pool is the highlight of the park. You will recall that Champagne Pool was created about 900 years ago by a steam eruption that connected a very deep hydrothermal aquifer with the surface . The Champagne Pool takes its name from the bubbles of carbon dioxide that constantly effervesce to the surface; however, that's where the relationship to a beverage ends. The water is about 75°C and acidic. Champagne Pool is famous among mineralogists and geochemists because it is the only place on Earth where we can see gold and silver being precipitated from a hydrothermal fluid. For example, the bright orange sulfur precipitates surrounding the edge of the pool contain arsenic (2%), antimony (2%), gold (80 ppm), silver (175 ppm), thallium (320 ppm), and mercury (170 ppm) (Lynne 2003). The truly interesting observation is that precipitation of these metals seems to be mediated by microbes (Jones et al. 2001).

We will start our day with a visit to Lady Knox Geyser. It erupts promptly at 10:15 a.m. every day with a little help from a box of soap powder. The story goes that prisoners at the nearby penal colony were using the hot spring to wash clothes. When they dropped their soapy duds into the spring for a rinse, they induced the first eruption, which scattered them and their clothes into the bush.

The science behind the soap is pretty simple. The geyser has two water chambers, a hot lower one and a cool upper one. The upper chamber is cooled by air because it has a larger opening to the surface. The lower one is heated by magma below. Overnight, the geyser's two chambers develop an unstable equilibrium (cool on warm). When soap is thrown into the upper water chamber, the lowered surface tension of the water destabilizes this equilibrium, allowing the hot water to rise explosively, erupting up to 20 m into the air. When the eruption is over, the chambers refill and the cycle repeats the next day for another group of curious tourists.

As you tour though the park, have a look at the wide range of hydrothermal features and consider the following when making notes in your notebook. Numbers refer to numbered signs in the park.

• Primrose Terraces, between 9 and 12. What kind of material makes up this feature? What evidence is there that it is still forming?

• Cliffs between 11 and 12. Describe these materials. How were they deposited?

• Thunder Crater, location 3. Describe this feature. How is this feature related to the surrounding craters?

• Frying Pan Flat between location 15 and 16. Look at the nodular materials exposed along here. What are they and how were they formed?

• Cliffs between 13 and 14. What kind of material is exposed in the cliffs. What is its origin?

• Champagne Pool, location 21. Champagne Pool is believed to have been tilted relative to an earlier shore line. Sketch and describe any evidence you can see for this.

• Lake Ngakoro Falls, location 18. Describe the materials exposed in the walls ere. Is it volcanic or related to the hydrothermal activity? Or something else?

• Alum Cliffs, location 14. Look at the sediments (yes, sediments) entering the lake here. If they were citified and later exposed by erosion, what feature would allow you to recognize that they were deposited by water and not volcanic in origin?

As always, additional, independent observations are required for full marks on the notebook.

Stop 2: Rotorua Geothermal Field and Kauriu Park
The city of Rotorua is built on impermeable lake sediments that formed in an ancient caldera lake (when Lake Rotorua was larger in a wetter past). These sediments overlay fractured rhyolites left behind when the Rotorua caldera blew itself up. The fracture porosity of the rhyolites makes them a good aquifer. Heat from magma far below warms the groundwater in the rhyolite. Some of this heated water rises through the lake sediments to the surface along the caldera margin faults to produce intense geothermal activity at Whakarewarewa, while the rest flow under the city as a plume of hot water held underground by the sedimentary cap. This plume extends from the Whakarewarewa thermal area to Government Gardens on the Lake Rotorua shoreline. Relatively shallow drill holes (50-150 m deep) can penetrate into the hot waters, which are under some pressure and flow easily to the surface and can be used to heat homes. In 1981, 550 private geothermal wells were in production. The withdrawals from these wells led to a decline in the activity of the Whakarewarewa thermal area, which is a major tourist draw. In response, the government began closing private wells in 1986 and subsequently developed a geothermal resource plan to closely monitor both water withdrawals and activity at Whakarewarewa. The plan appears to have been successful: Whakarewarewa is back in action. However, there has been some increase in undesired steam eruptions such as those in Kauriu Park, across the street from the hospital.

Day 14—Thursday 27 November. Thanksgiving. Weather permitting, we'll travel to Whakatane (about 85 m from Rotorua), then travel another 48 km into the Bay of Plenty to visit Whakaari (White Island). Our day will conclude with a Maori Thanksgiving feast.

Whakaari (White Island)—Whakaari is the most active of New Zealand's volcanoes. It is also the site of one of the three major volcanic disasters in New Zealand history, when 11 sulfur miners were killed in 1914. (The other two disasters are already familiar to you: the 1886 Tarawera eruption and the 1953 Tangiwai rail disaster.)

Whakaari is the summit of a large (16 by 18 km) submarine volcano. Only about half of the volcano's height and a small proportion of its volume are above sea level. Whakaari is a stratocone, much like Ruapehu, a fact that is easily observed by looking up at the walls of the crater where you can see them in cross section. The central crater was formed in prehistoric times by the collapse of three overlapping subcraters (Fig. 14). The eastern subcrater was formed first and now contains only minor hot spring activity. The central subcrater contains the Donald Mount fumaroles, and the Noisy Nellie and Donald Duck craters and fumaroles. The western subcrater contains most of the eruption sites that have formed since 1960 and is the main focus of activity today [Cole, 1991 #17].

Notebook Assignment: As we approach Whakaari, make a sketch of the internal structure of the crater walls exposed in the blown-out side of the crater. Describe the evidence that demonstrates that this is a stratocone.

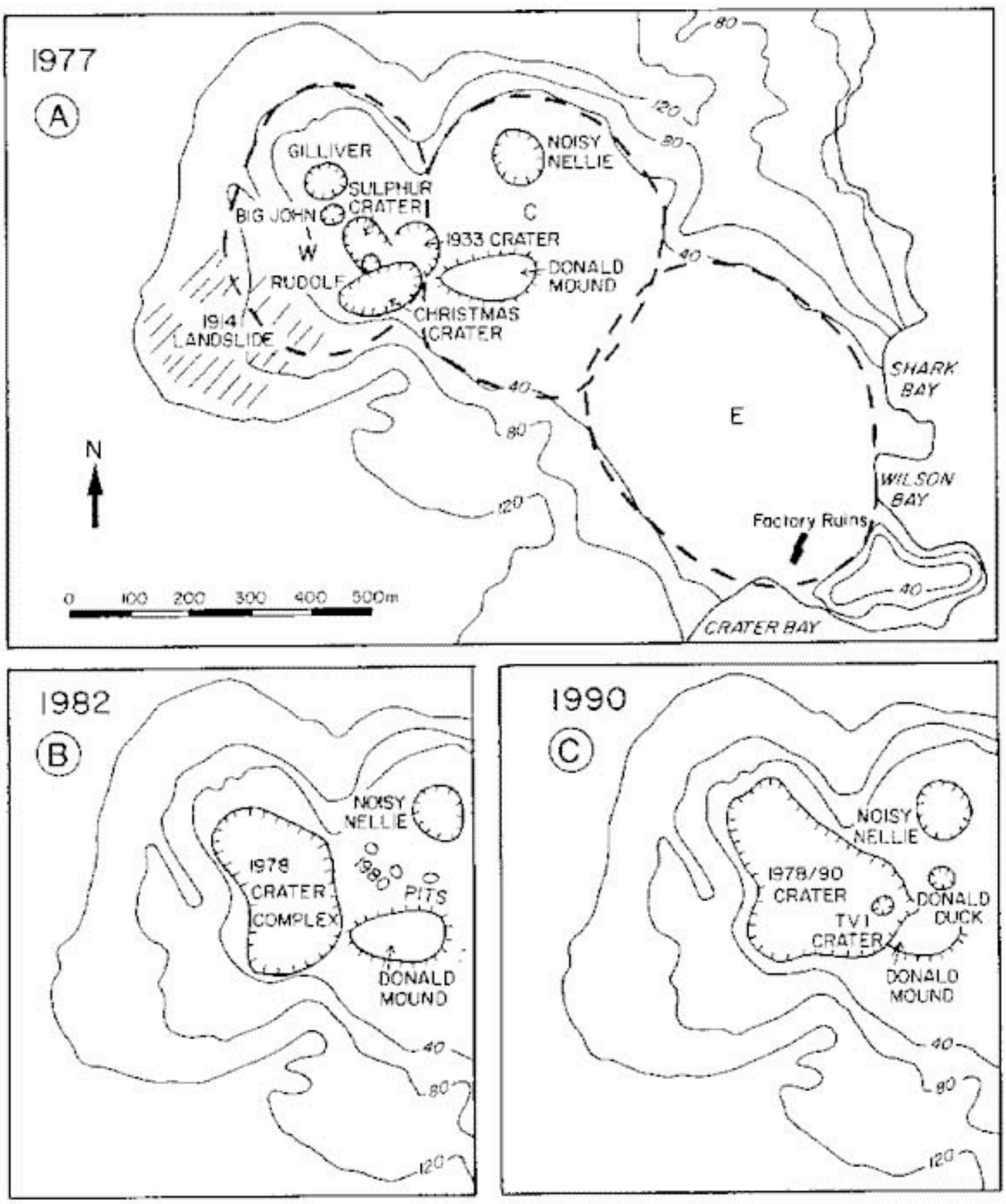


Figure 14: (A) Map showing positions of the three subcraters making up the main crater floor at Whakaari (E = eastern, C = central, W = western), with locations of vents within the western subcrater in 1977. (B) and (C) show the changes that have occurred since 1977, 1982, and 1990. TV1 Crater formed in October 1990, and is typical of the six short-lived new vents that have formed in 1978/1990 Crater since 1983.

Ash layers in ocean floor sediment drill cores record activity at Whakaari as far back as 16,000 years ago, but the volcano has certainly been active for much longer than this. No prehistoric ash from Whakaari has ever been identified on the mainland. Continuous low-level activity and intermittent small eruptions have been reported since the beginning of monitoring in 1826. The crater was often flooded by hot lakes until it was permanently drained in 1913 to make way for sulfur mining. In September 1914, the southwest corner of the high crater collapsed; the resulting hot avalanche buried 11 miners and destroyed buildings and equipment at the eastern end of the crater. You can still see mounds of avalanche debris. Since 1914, new vents have formed in the west and central sections of the crater and have produced intermittent steam and ash eruptions. "1933 Crater" (Fig. 14A) formed in that year during an explosive ash eruption; "Noisy Nellie Crater" formed prior to January 1947, "Big John Crater" grew to 50 m in diameter during eruptions between 1962 and 1965. A steam and ash eruption in November 1966 accompanied formation of the 60 m "Bulliver Crater. Rudolf vent grew from a fumarole during ash eruptions in 1968 -- some ash fell on the North Island during these eruptions. Two years later, a single explosive eruption formed "1971 Crater". The volcano was quiet until 1976, when the longest and largest period of eruptions began. This eruptive phase continued until 1982. At some times during this period, fountains of glowing lava produced a glow in the night sky visible from the mainland along the Bay of Plenty. Since 1982, activity has been restricted to ash and steam eruptions (Cole et al. 1991). Whakaari last erupted from beneath the crater lake in 2000. Today, Whakaari is at Level 1 alert. Beginning in late October, the crater lake has risen about 15 m (within 9 m of overflow) and its temperature remains high (57°C—GeoNet alert 23 October 2008) and an area of high surface heat has developed and spread on the south side of the Main Crater. These changes likely reflect rearranging of the hydrothermal plumbing under the mountain, which, in turn, may reflect magma on the move.

Whakaari is capable of generating several different types of eruptions. Explosive steam or gas eruptions occur when groundwater comes in contact with hot rock or magma. Such eruptions occur with no warning and may happen during periods of either quiet or increased activity. Such explosions commonly launch blocks of material, hot gasses and ash into the air. Particularly large and violent steam explosions occur when groundwater-saturated crater floor rock collapses into the magma conduit. The resulting steam explosions have produced the highest eruption columns recently observed (3-4 km in 1977). Such explosions may also form pyroclastic flows. Although the effects would be devastating within the crater, only people in the crater at the time of an eruption will be affected (Cole et al. 1991).

Because the crater floor is underlain by wet volcanic debris, the eruption of lava flows at Whakaari is unlikely. Instead, the rise of magma into the wet sediments would produce explosive steam eruptions. The eruption of lava flows would require the rise of large volumes of magma to dry out the crater fill, but the current pattern of activity suggests that this is unlikely in the foreseeable future.

Debris avalanches are another story. Parts of the nearly vertical walls are unstable, particularly at the western end. The 1914 avalanche came from the southwest wall of the crater and similar events are almost certain to happen in the future. Debris avalanches are likely to be triggered by strong earthquakes or large volcanic explosions. They may also occur in response to heavy rainfall that saturates and lubricates the unstable wall material. Debris avalanches into the sea could also occur on the steep outer slopes of the volcano (Cole et al. 1991). Such an avalanche could produce a tsunami, although there is no evidence that such an event has occurred in the past.

Gasses are constantly emitted from the craters and fumaroles on Whakaari. Several hundred to several thousand tons per day are usual rates of emission. The most common gasses are steam, CO_2 and SO_2, with small quantities of halogen gases (chlorine and fluorine). The acid gasses (particularly SO_2) combine with water in the steam/gas clouds to form liquid acid droplets that can sting the eyes and skin and affect breathing (Cole et al. 1991). As a consequence, you will be issued a respirator to wear in the crater if you choose. Acid droplets can also damage cameras, electronic equipment and clothing. It's a good idea to carry your camera in a ziploc bag and leave your other electronics at home. Also, don't wear clothes that you would hate to have damaged, particularly cotton, which may be very vulnerable to acid damage. Volcanic gases on Whakaari are discharged at temperatures between 100°C and 800°C; anyone falling into a vent would be rapidly cooked. So try to walk with your eyes shut against gas clouds and don't leave the trail!

Although Whakaari has apparently never produced a large eruption, recent work suggests that is might be capable of relatively large events. Modeling of the amount of magma needed to sustain both the gas emissions recorded and the heat flow observed suggest that a magma body several tens of cubic kilometers may lay beneath the mountain. Eruption of even a portion of this body would constitute a "major eruption" (Cole et al. 1991).

What to do in an eruption

Whakaari is monitored around the clock and tour boats will not leave Whakatane if there is concern. However, as noted above, violent steam eruptions can occur without warning. If one should occur, try to stay calm, stay together with the group and follow the instructions of your guides and leaders. Put on your mask and move as quickly as possible toward the eastern (factory) end of the crater floor. This area has been safe in all except the largest eruptions since 1976. If you are caught in steam and ash clouds, take cover where you are behind rocks, put on your mask and stay put until visibility improves. Remember, debris may fall from above, so keep your hard hat on at all times and cover your head.

Following our return to Rotorua, clean up quickly because we will be departing directly for our Maori Thanksgiving Feast.

Tamaki Maori Village—Although the Maori experience in New Zealand differs significantly from the Aboriginal experience in Australia, many Maori teeter on the cusp of poverty and many young people may lack hope for the future and pride in their past. In 1989, Mike and Doug Tamaki were two such young men. Growing up outside of Rotorua, they saw that the Pakeha were making tons of money imitating Maori culture for the tourists. They believed they could do a better, more authentic, job at interpreting their culture for visitors, but no bank would give them the loan to get started. Mike set his sights on his brother's Harley, and, once Doug was convinced, they sold the bike and bought a van that could pick up visitors and bring them to the pre-European Maori village they and their friends and family were building. Skeptics believed that the location was too far off the beaten track, that preparing a traditional hangi dinner would be too expensive and time-consuming, and that visitors just wouldn't come. However, they now host more than 100,000 people a year who come to encounter a people and a culture that is thriving and proud.

Our evening will go something like this...We will be picked up in a coach that will transform into a Waka (Maori seafaring canoe). The idea is that we are a visiting tribe that is approaching the Tamaki village. Our guide will tell us about the rules and protocol for visiting. As is traditional, no one can enter the village until they have been challenged (remember the Maori were an aggressive and territorial people), the leader found worthy, and the welcoming ceremony (Powhiri) performed. If we pass the test, a teka (peace offering) is given and received. If all goes well (no laughing!) we will enter the village and see a wide range of people demonstrating traditional life crafts and daily activities. We'll make our way to the Wharenui, a meeting house that represents the ancestors. Speeches, songs and dances will celebrate the arrival of new friends. After the performance, we'll move to the dining room for a tradition hangi meal. The hangi is cooked in the earth on hot rocks for three to four hours. This is a traditional cooking method, which is shared with many Polynesian cultures. Rocks are heated to white hot using only native hardwood timber. Then, they are put into a pit dug into the ground. Baskets of meat are put directly onto the hot stones, then vegetable baskets and the pudding on top. A wet cloth is placed over the food and it is covered with dirt. The food cooks by a combination of steaming and smoking, which gives the hangi its distinctive flavor. Following the meal, a closing ceremony bids farewell to the new friends. We'll board our Waka and head home.

Day 15—Friday 28 November. Today is a wrap-up day. Following course evaluations, you will have the day free to study, call home (it's Thanksgiving in the States), finish those last geo post cards (due by 4 p.m. today) or explore Rotorua on your own. Prof. Arens and Kendrick will be available all day to answer questions and we will organize a question-and-answer session if you wish. The exam will begin at 4 p.m. Following the exam, the program has officially ended and you may depart. However, supper, hostelry, breakfast tomorrow and the bus ride to Auckland are still covered by the program.

Day 16—Saturday 29 November. Bus will depart for Auckland international airport shortly after breakfast. We will arrive approximately mid-day and drop you off at the airport. Please plan to make your own arrangements from this point onward.

In conclusion, it has been a great pleasure to have you as part of the program. We have been continually impressed with your enthusiasm, curiosity, intelligence, resilience and willingness to work together in a constructive way. The latter is no small accomplishment in a group as diverse as ours. As we said when we first gathered in Brisbane back in August, we do a lot of work to make sure things will go smoothly and be enriching for you, but the success of the program rests in the hands of the students. We thank you for making this program a success! N.C. Arens and D.C. Kendrick

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Rhizocarpon calibration curve for the Aoraki/Mount Cook area of New Zealand

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ABSTRACT: Development of *Rhizocarpon* growth curve from the Aoraki/Mount Cook area of New Zealand provides a means to assess Little Ice Age glacier behaviour and suggests approaches that have wider application. Employing a sampling strategy based on large populations affords the opportunity to assess which of various metrics (e.g. single largest, average of five largest, mean of an entire population) best characterise *Rhizocarpon* growth patterns. The 98% quantile from each population fitted with a quadric curve forms a reliable representation of the growth pattern. Since this metric does not depend on the original sample size, comparisons are valid where sample strategy must be adapted to local situations or where the original sample size differs. For the Aoraki/Mount Cook area a surface 100 years old will have a 98% quantile lichen diameter of 34.3 mm, whereas a 200-year-old surface will have a lichen diameter of 73.7 mm. In the Southern Alps, constraints from the age range of calibration points, the flattening of the quadric calibration curve and ecological factors limit the useful age range to approximately 250 years. Copyright © 2005 John Wiley & Sons, Ltd.

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KEYWORDS: lichen; calibration; New Zealand; Little Ice Age; glacier.

Introduction

Lichen growth rates are a common tool used to reconstruct the chronologies of very recent landscape activity. However, only a limited number of such attempts have been made in the southern hemisphere (e.g. Burrows and Orwin (1971); Gellatly (1982); Rodbell (1992); Bull and Brandon (1998); Winchester and Harrison (2000); Winchester *et al.* (2001); Winkler (2004)) with the Southern Alps of New Zealand (Fig. 1) receiving virtually all of the attention for *Rhizocarpon*. Here, Burrows and Orwin (1971) first considered the largest diameter lichen on five moraines of the Mueller Glacier, fit a linear curve to these and found the largest lichen on a 100-year-old surface to be 53.5 mm in diameter. This curve was questioned because Birkeland (1981) considered the age assignment of two calibration moraines to be inconsistent with their degree of soil development relative to older and younger moraines.

Gellatly (1982) employed multiple relative dating techniques to investigate moraine sequences in the Aoraki/Mount Cook area. Age assignments for the moraines incorporated the modal value of the weathering rind thickness (Chinn, 1981). Using these ages Gellatly (1982) added new lichen points and recalibrated the Burrows and Orwin (1971) curve. For example, on the Tasman Glacier, a surface first suggested to be ca. 360 years old was reinterpreted to be 840 years old, whereas on the Mueller Glacier a ca. 350-year-old surface was reinterpreted to be 1830 years old. These results imply rapid lichen growth for 200 years with a slower, linear growth until 1000 years. The largest lichen on a 100-year-old surface was suggested to be some 32–33 mm in diameter or approximately half the size suggested by the Burrows and Orwin (1971) calibration.

Bull and Brandon (1998) employed a population-based approach to study rockfall events along the northern portion of the Southern Alps. Based on the assumption that synchronous rockfall events can be identified across multiple sites, they suggested that colonisation occurs within 5 years, that rapid growth is completed in 24 years, and that a subsequent linear growth rate of 15 mm per century would yield an average population size of lichen on a 100-year-old surface of 22 mm. This great growth interval is considerably shorter than has been identified in other studies. Bull and Brandon (1998) further suggested that the growth rate curve applies across a diverse range of climate, altitude and substrate lithology conditions.

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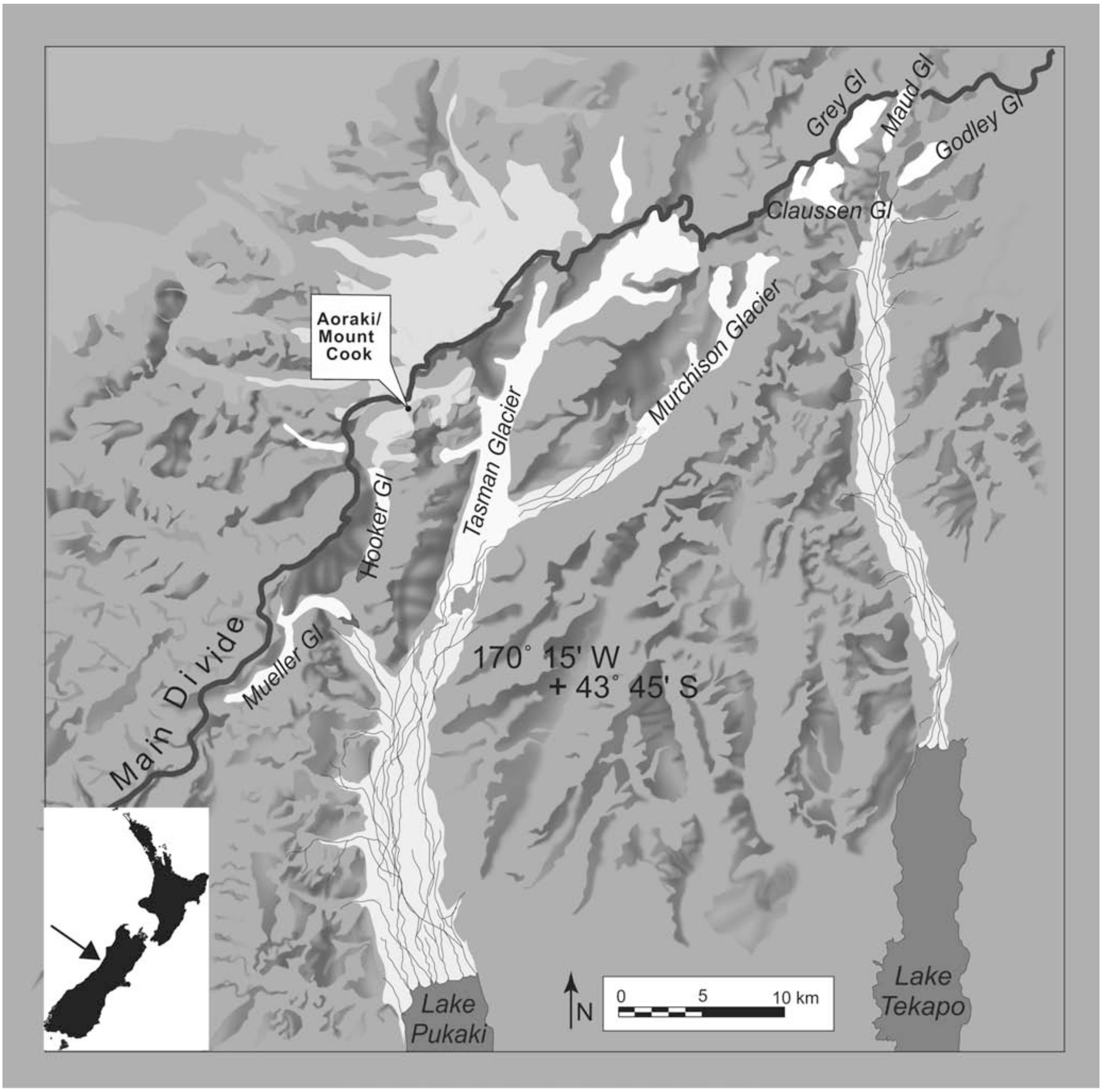

Figure 1 Shaded relief map of the Aoraki/Mount Cook area of New Zealand and surroundings

Because of these uncertainties, we undertook to establish an independent lichen calibration curve for Aoraki/Mount Cook National Park based on large sample sizes. We took advantage of this sampling approach to identify a robust metric to describe these populations.

Setting—Methods

Geography of the Southern Alps

The primary control on the geography of New Zealand is the backbone of the Southern Alps. This northeast to southwest trending mountain range typically reaches 2000 to 3000 m in height with Aoraki/Mount Cook at the maximum elevation of 3744 m. Local bedrock holding up these mountains is largely a massive sandstone/greywacke that may have undergone low-grade metamorphic alteration near major faults. Collectively these rocks belong to the Torlesse Supergroup (Cox and Begg, 1999), and all facies of these rocks are present on the moraines in the study area.

The Southern Alps form a natural barrier in the southern westerly circulation belt and traps moisture on the western side. The maximum rainfall on the western side of the range can exceed 10 m (Wratt *et al.*, 2000). Moreover, because of the spillover effect precipitation values on the eastern side of the range typically exceed 3 m within 15 km of the Main Divide (Fig. 2). Precipitation is abundant throughout this study area and not likely to be a limiting factor in the growth of lichen. The spillover effect also funnels wind into the valleys. The exposed, up-valley sides of boulders are often barren of vegetation whereas the downwind sides have oxidation rinds and lichen or moss vegetation cover.

Rhizocarpon have a preferred altitude range. The altitude ranges of the foreplanes and lateral moraines sampled for this

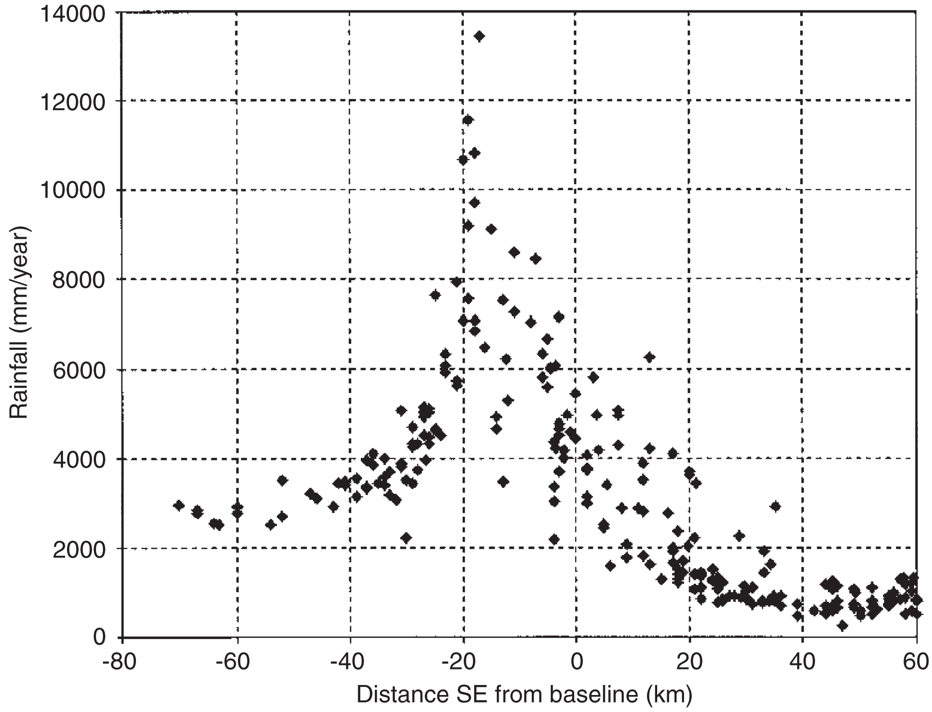

Figure 2 Rainfall distribution across the main divide of the Southern Alps, after Wratt *et al.* (2000). The main divide depicted here is the linear trend of the mountains not the many local convolutions of the mountain crest line. Our sample sites would plot within 10 km of the divide on this diagram. The spillover of moisture from the main divide provides more than 2 m precipitation to all areas

study include: Mueller Glacier (780–880 m), Hooker Glacier (880–1000 m), Tasman Glacier (720–960 m), Murchison Glacier (1020–1400 m), Classen Glacier (980–1200 m), and Godley Glacier (1000–1220 m). Field observations indicate that *Rhizocarpon* are rare above these elevations. The lowest foreplanes lie within the montane zone (Wilson, 1996) and although human activity has cleared the forest, shrub and small tree growth is being reestablished and thus reclaiming areas colonised by the study lichen, *Rhizocarpon*. Sites located in the 800 to 1100 m elevation range proved most suitable. All of these foreplanes are east of the Main Divide and front the above-noted glaciers, which are among the 10 largest in New Zealand.

Figure 3 Photograph of the Classen and Godley margins taken by G.E. Mannering in 1892. Note that the Godley ice level has already dropped from the well developed trimline in the centre part of the image. (Photograph 16519, Kennedy collection, Canterbury Museum. Reproduced with permission)

Basis for age assignments

To establish our calibration curve, ages for various landforms were extracted from one of three data sources: first-hand accounts from mapping and mountaineering expeditions, historical photographs, and tree ring counts at Mueller Glacier. The first published expedition report is that of Haast (1879) who surveyed the geology of the Canterbury district and visited all glaciers considered here in AD 1862. E.P. Sealy visited the region in AD 1867, taking photographs, and made the first maps of the glacier margins. These maps are included in Haast (1879). Examples of historic photographs are shown in Figs 3 and 4.

T. N. Brodrick undertook a topographic survey through the mid-1890s. Brodrick (1894, 1905) also traced the positions of boulders on the glacier surface and thus provided the first glaciological measurements on the Mueller Glacier (Ross, 1892). Other accounts describing glacier positions include Harper (1893), Mannering (1890), and Fitzgerald (1896). Du Faur (1915) was the first woman to climb extensively the Southern Alps and she describes a flood on White Horse Hill at Mueller

Figure 4 Photograph of the Classen–Godley margins taken from Mt Acland by H.O. Frind in 1914 and used to constrain points C23 and C32 (Table 2). (Photograph 16521, Kennedy collection, Canterbury Museum. Reproduced with permission)

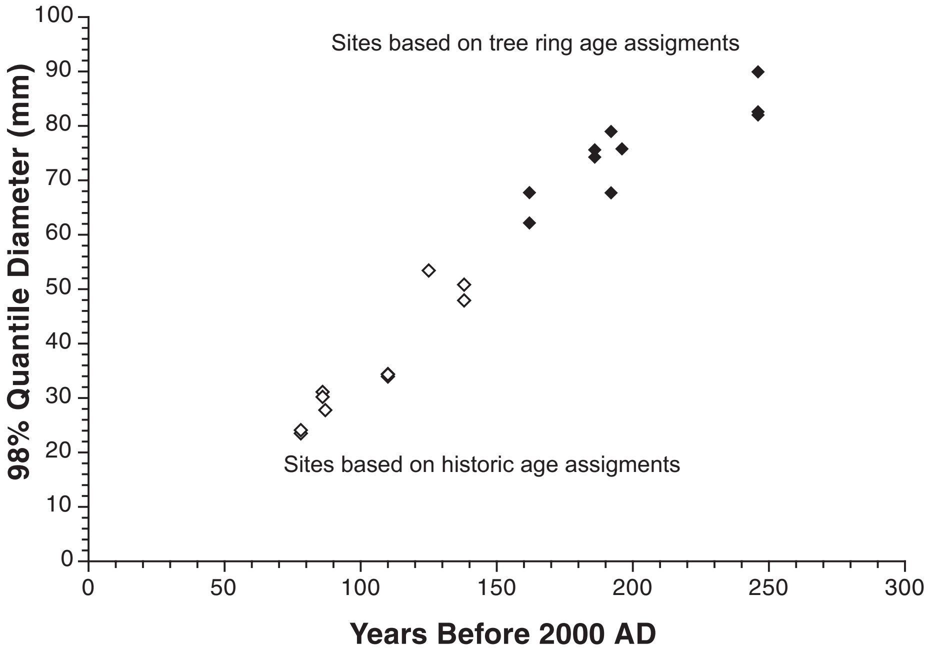

Figure 5 Comparison of lichen diameter and age where age is derived from historic means (open) and tree-ring means (closed). The general trend indicates close correspondence between the two different age assignments supporting adoption of the tree-ring age assignments

Glacier (Sample M76, Table 2). In the Godley valley H.O. Frind took photographs and Fletcher (1921a, 1921b, 1922, 1923, 1925) made several climbing trips to the Classen–Godley Valley and reported on changes in ice margin position. Gellatly (1985) reviews these and other sources of historical information about these glaciers.

Lawrence and Lawrence (1965) noted that the moraines of the Mueller and Hooker Glaciers were such that 'we could see and understand the history of their (tree) variation in size'. Coring of *Phyllocladus alpinus* (mountain celery pine) provided eight sites defining the expansion and retreat of the Mueller Glacier. This work has not been widely referenced and it has long been recognised that tree age only provides a minimum age for deglaciation because of lag in tree growth subsequent to deglaciation. The reported ages are simple ring counts and the authors do not assign any other correction or error. However, the results of Lawrence and Lawrence (1965) are provisionally accepted here for the following reasons.

1 They are internally consistent showing a progression consistent with the relative ages of the moraines. Two inset moraines on the south side of Mueller Glacier yield an outside age of AD 1794 and inside ages of AD 1838 and 1839. Another pair of ages on an eastern moraine of Mueller Glacier yielded matching ages of AD 1804 and 1808.
2 The tree ring record extends back several hundred years. For the same eastern moraine noted above Gellatly (1984) suggests an age of 2940 ± 760 years. If so, the trees would likely be older than AD 1804 or 1808. A tree that started growing on nearby White Horse Hill about AD 1445 (Lawrence and Lawrence, 1965) demonstrates that trees grew in the area well prior to AD 1800 and indicates trees in this area can be at least this old.
3 The morphology of trees changes across a major geologic boundary. A key site in the Lawrence and Lawrence (1965) report lies at the contact of glacial material from Mueller Glacier and the flank of Mt Wakefield. According to Lawrence and Lawrence (1965) ice advanced to that position after AD 1730 and remained there from AD 1745 to 1765, whereas Gellatly (1984) suggests an age based on weathering rinds of 3350 ± 850 years for the same site. The current average diameter of the five largest specimens on the moraine segment are 68.7 cm for *Phyllocladus alpinus* (mountain celery pine) and 59.4 cm for *Podocarpus hallii* (Hall's totara), whereas on the adjacent mountain slope the averages are larger at 81.1 and 94.9 cm, respectively. Although tree diameter can be a problematic absolute indicator of tree age, if this landform were more than 3000 years old, one would expect the development of even-sized stands, as several generations of trees would have occupied both locations. Moreover, it is in just these contact settings that tree rings provide both expansion and retreat data (e.g. Heusser (1956)) as has been reported elsewhere.
4 The tree ring ages provide a conformable pattern with the historical ages. Plotting the lichen diameter of the 98% quantile vs. age (Fig. 5) show that the proposed tree rings calibration sites form a consistent trend with the ages obtained from the historical observations. A simple regression line through the tree ring points and the origin yields a slope of 0.34 ± 0.028 whereas a similar regression through the historical points has a slope of 0.37 ± 0.033. There is no major offset or change in fitted curve as would be expected if the tree ring observations were significantly younger than the surface they occupy.

Thus, because several internal consistency checks agree we provisionally accept the tree ring ages (Lawrence and Lawrence, 1965) and employ them to develop the calibration curve described below.

Sampling strategy

Various geomorphic landforms provide the sample areas. The lichen age on any landform contains a potential offset because of time needed for the surface to stabilise following deposition and sampling avoided active slopes where local patches of material were moving downslope. Stable landforms may be difficult to quantify exactly. We found active lichen thalli on superglacial drift on both the Tasman and Murchison Glaciers. However, these lichen were destroyed when the source boulders slumped into the developing karst topography. Multiple sample sets per landform serve as cross-checks. Geologic maps of the glacial foreplains (Schoenenberger, 2001; Black, 2001; Smith, 2003) link historic references and individual landforms to individual lichen measurements. These maps allowed tracing of same age landforms, identification of crosscutting relationships, and connection of landforms of different origin but of the same ages, such as meltwater channels active when the moraine formed. In addition to moraines, channels and point bars of relic outwash deposits were also considered. Because of their low relief, meltwater landforms are less likely to undergo post-depositional surface changes. Because the frontal glacier retreat progresses toward proximal areas, lichen on moraines further downstream must be older than lichen up flowline. This geomorphic approach set the lichen samples in a relative chronologic order.

The lichen of interest was *Rhizocarpon section Rhizocarpon* and no attempt was made in the field to distinguish among individual species. The samples were measured in January and February of the austral summers of AD 2000, 2001 and 2002. Ages reported here are relative to the year AD 2000.

Bull and Brandon (1998) present powerful arguments to enhance lichenometry by the use of digital calipers and large sample sizes. This included a suggestion to measure the lichen data with the fixed-area largest lichen or FALL technique (Bull and Brandon, 1998). In this strategy, a number of fixed areas were examined to identify the largest lichen within each area and the longest diameter was measured. Following the suggestion of Bull and Brandon (1998) we recorded measurements made with digital calipers. A collection of these areas, typically 100, forms the basis for a single count or sample. In practice, the surface area afforded by a boulder with an intermediate axis of at least 25 cm was taken as the fixed area. Other information recorded was direction aspect, lichen quality, landform position, and operator. Traverses along zones 2 m wide were undertaken until the target sample size was tallied. Most of the sample areas ranged from 10 to 100 m^2. Because Bull and Brandon (1998) sought to identify the individual events that contributed to a composite landform and we sought the age of individual landforms, subsequent analysis differs.

The age control points were not identified prior to field sampling. Rather we undertook an extensive measurement campaign embedded with our geomorphic mapping. Historical maps and documents were then examined to identify landforms of known ages and the collected samples from these were taken for calibration purposes. Thus historical or tree ring data provided calendar ages for 21 sites which were characterised by some 2359 individual lichen measurements. Each sample was examined within the geomorphic context of surrounding samples and where several samples per calibration landform was available, extreme outliers (generally those samples with smaller sizes than correlative samples) were excluded. Specific sites and references are in Table 1.

Sample representation

This sampling strategy provided the opportunity to assess the performance of various metrics that might characterise each sample. These metrics fall into two broad groups: sample mean or extreme. Representation of lichen on a population basis is appealing because it reduces issues with extreme values. However, fitting lichen populations into commonly used statistical distributions has proved challenging (e.g. Innes (1986)) with even the form of the best distribution still open to debate. Bull and Brandon (1998) note that New Zealand lichen samples differ significantly from a simple Gaussian distribution and suggest superimposing two Gaussian distributions as a solution. Another challenge with a population approach is that the relationship of the entire population to age is unlikely to be linear. The continued addition of smaller lichen will prevent the mean sample size from increasing as quickly as the individual lichen size and the cumulative curve will plateau. A nearly flat line is not desirable for a calibration curve.

To test whether a common distribution could describe these lichen samples, four distributions were considered: normal, log-normal, Gumbel, and Weibull. Each distribution was fitted to a set of 112 samples from the Classen and Godley Glacier forefields and a likelihood-based goodness of fit was computed for all four distributions. That is, for each sample we computed the likelihood that any of these distributions provided the best fit, and picked the distribution with the highest probability that fit the sample. This exercise showed that a log-normal distribution best fits the lichen samples in 50.0% of the cases whereas a Weibull distribution was the best fit for 43.8% of the cases. The normal or Gaussian distribution is the best descriptor for only 6.3% of the samples and in no case did the Gumbel distribution provide the best fit (Table 2). The inability of any simple population distribution to describe these lichen populations suggests employing any of these may be problematic and may explain why various authors have employed different distributions. A histogram for two cases constitutes Fig. 6. For comparison purposes a simple log-normal mean was chosen to represent an entire sample population.

A second approach for analysis is to employ some extreme value. However, in addition to cautions about extreme values in general, the size of the largest lichen depends critically on the total area sampled (Innes, 1984). Since, the largest thalli in the entire sample set has often been employed it is considered here. The 'largest' lichen reported here might be difficult to compare directly with other efforts because it is the largest of only 100 individuals whereas in other cases, the largest lichen may represent several hundred or several thousand individuals. To illustrate, at the Mueller Glacier five thalli counts on a single well-developed moraine yielded a largest individual lichen size of 75.60, 49.39, 61.11, 56.79 and 76.73 mm. An independent search for the largest lichen along an adjacent 500 m section of the moraine uncovered a maximum lichen diameter of 75.93 mm. Thus only two of the five samples have a similar 'largest' size as that recorded over an extensive area.

The average of the five largest lichens in the population set avoids potential problems if the largest lichen is not representative of the geomorphic surface. Thus, it is commonly employed; but again this metric depends on the total area and hence the total number of individual lichen thalli sampled. A concern with the 10 largest method is that the sample may contain enough small-size individuals introducing the same issues as noted for entire populations.

Another extreme value approach is to track some quantile of the entire population. For example the 98% quantile represents the size of the single thalli that is larger than 98% of the sample population immaterial of the sample size. This metric was selected for consideration because it is robust; it depends on a sample population but does not depend on the distribution of the sample. Moreover, it can be computed for any sample size allowing for comparison of different sample sizes. Here we simply employed PROC UNIVARIATE of the SAS software package with the default method of computing quantile SAS. In the example cited above at Mueller Glacier, the 98% quantile results were 55.13, 48.27, 56.77, 51.95 and 39.70 mm, respectively. This example illustrates that the 98% extracts a

Table 1 Calibration points

Glacier	Sample ID	Latitude	Longitude	Age AD	Year BP	Basis	Comments	Sample size	Largest	98%	5 largest	10 Largest	Log-normal
Sites where age determine by historical means													
Classen	C02	−43°30.901′	170°28.661′	1862	138	Haast, 1879, drawing C-097-171	This is the inner of two fresh moraines	101	61.68	47.93	51.71	47.18	22.70
Classen	C23	−43°30.730′	170°28.709′	1914	86	Frind, 1914, Kennedy collection image—16521	Ice thinning to expose buried lateral	100	42.22	31.12	31.56	28.03	12.88
Classen	C31	−43°31.047′	170°28.922′	1862	138	Haast, 1879, C-097-171	Innermost of fresh moraine sets	100	54.37	50.83	48.86	44.46	19.80
Classen	C32	−43°30.765′	170°28.861′	1914	86	Frind, 1914, Kennedy collection image—16521	Ice front position in photograph	100	31.66	30.20	29.49	25.72	12.25
Classen	C54	−43°30.838′	170°29.294′	between 1862 and 1888	125	On Haast 1879, C-097-171 (1862), but not shown on Brodrick, 1894	Inner portion of channel—lowest and thus youngest occupied	100	57.43	53.43	52.19	45.27	24.51
Godley	G18	−43°28.922′	170°30.527′	1922	78	Sutton-Turner photograph, PA1-f-074-064	Shows ice pulling off mound in the mouth of Fitzgerald Stream. From records could be any of 3 Fletcher trips between 1920 and 1924	100	23.67	23.51	23.42	22.23	11.30
Godley	G42	−43°28.922′	170°30.527′	1922	78	Sutton-Turner photograph, PA1-f-074-064	Replicate count of G18	100	26.77	24.10	24.32	22.38	11.05
Mueller	M28	−43°42.895′	170°05.940′	1890	110	Fitzgerald, 1896, p. 112, photograph, Brodrick, 1905, C-1, p. 112–113, map	This older age assignment than prior workers. same moraine as M29. M62 a replicate count	126	43.77	34.41	35.94	33.21	21.66
Mueller	M29	−43°42.900′	170°05.863′	1890	110	Fitzgerald, 1896, p. 112, photograph, Brodrick, 1905, C-1, p. 112–113, map	Adjacent count to M28	100	45.12	33.95	35.04	31.87	20.03
Mueller	M62	−43°42.895′	170°05.940′	1890	110	Fitzgerald, 1896, p. 112, photograph, Brodrick, 1905, C-1, p. 112–113, map	Replicate of M28	150	43.71	34.33	36.61	34.27	19.26
Mueller	M76	−43°41.538′	170°06.156′	1913	87	Du Faur, 1915, p. 209	White House Hill Flood	200	31.01	27.78	29.30	27.38	14.45
Sites where age determine by tree ring means													
Mueller	M101	−43°43.140′	170°06.125′	1754	246	Lawrence and Lawrence, 1965, old camp site	Lateral connection to M321 and M322	100	101.26	89.93	82.59	68.75	32.62
Mueller	M31	−43°43.111′	170°05.911′	1814	186	Lawrence and Lawrence, 1965, 'ice gone by 1814'		104	76.55	74.26	74.41	69.34	39.79
Mueller	M32	−43°43.123′	170°05.722′	1814	186	Lawrence and Lawrence, 1965, 'ice gone by 1814'		101	80.22	75.60	75.03	69.16	39.98
Mueller	M321	−43°43.202′	170°06.225′	1754	246	Lawrence and Lawrence, 1965, old camp site	Lateral connection to M101 and M322	100	86.09	82.00	79.96	74.41	39.39
Mueller	M322	−42°43.227′	170°06.142′	1754	246	Lawrence and Lawrence, 1965, old camp site	Lateral connection to M101 and M322	100	99.99	82.59	81.83	74.87	40.40
Mueller	M48	−43°43.012′	170°05.880′	1838	162	Lawrence and Lawrence, 1965, 'formed by 1838'	On north (proximal) side moraine segment of M80	125	78.94	62.17	67.43	61.72	34.14
Mueller	M53	−43°42.620′	170°06.235′	1808	192	Haast, 1879 p. 32, written description Lawrence and Lawrence note 'ice gone by 1808'	The M53–M57 sequence most likely are about the same age—also see M311 series—This seems to be the sequence that deglaciated fast. Single point near tree ring sample	126	80.66	78.97	75.32	68.04	35.99
Mueller	M54	−43°42.492′	170°06.130′	1808	192	Haast, 1879 p. 32, written description Lawrence and Lawrence note 'ice gone by 1808'	Sequence deglaciated rapidily, this is the closest sample to tree site	159	78.63	67.70	71.86	68.59	33.18
Mueller	M56	−43°42.205′	170°06.423′	1804	196	Haast, 1879 p. 32, written description Lawrence and Lawrence note 'ice gone by 1804'	Sequence deglaciated rapidly	67	85.38	75.78	76.51	72.56	39.25
Mueller	M80	−43°40.510′	170°07.182′	1838	162	Lawrence and Lawrence, 1965, 'formed by 1838'	On south (distal) side moraine segment of M48	100	83.21	67.74	67.81	60.77	25.82

Notes: Location reported in WGS 84 datum. Present taken as AD 2000. Lichen diameter reported in mm. Geomean is the geometric mean of the sample. Photograph 16521 housed at the Canterbury Museum, Christchurch, New Zealand. Photograph PA1-f-074-064 housed at the Alexander Turnbull Library, Wellington, New Zealand.

Table 2 Best-fit distributions

Distribution	Classen	Godley	Combined percentage
Normal	4	3	6.3
Log-normal	36	20	50.0
Gumbel	0	0	0.0
Weibull	28	21	43.8
N	68	44	

Note: For each glacier the number reported is the number of samples for which the specified distribution provides the best goodness of fit.

more reproducible and consistent result than a metric of 'the largest lichen'.

Results

To determine the most robust calibration curve, we considered the diameter of the single largest thalli, the diameter of the 98% quantile, the average diameter of the five largest, the average diameter of the 10 largest, and the log-normal mean of the diameter for the entire population (Fig. 7). For each of these metrics the calibration data set age was regressed against diameter and a curve fitted with both a linear regression and a second-order quadratic polynomial. R^2 values ranged between 0.84 and 0.98 (Table 3). For all five metrics, the linear regression always has a lower correlation (R^2) than the quadratic regression thus we choose quadratic form because of its higher correlation.

On the basis of simple R^2 values the mean of the five largest individuals provides the best fit ($R^2 = 0.98$, Table 3). There are several reasons to support this choice for a working calibration curve. First, this metric reduces problems with unique or outlier individuals as they are relegated to a small portion of the sample. Second, the five largest metric provides good resolving power. However, the average of the five largest for a particular sample depends on the sample size (Innes, 1984); the absolute value will increase with larger sample sizes. If one were to take the five largest on a given landform, any viable comparison would require that the sample size be the same. Thus, this metric is well suited where the total sample populations have the same number of individuals.

In cases where it is desirable or necessary to compare sample sets of different sizes, the 98% quantile may be a more suitable metric. Its correlation coefficient is nearly as strong as the five largest ($R^2 = 0.96$, Table 3) and has many of the same properties as described above. In addition, it is independent of sample size. Since the extreme metrics provide a better correlation between age and lichen diameter than does the mean of the entire sample size as argued by Bull and Brandon (1998) the 98% quantile is adopted here.

We note a limitation of this particular calibration curve: it has younger and older useful limits imposed by the age distribution of the calibration points. On the younger end, a simple extension of the curve (Fig. 7) suggests a 40-year colonisation period for this lichen. However, direct observations indicate a faster colonisation. This may reflect a dearth of suitable younger surfaces because the rapid and dynamic retreat of these glaciers has left lakes, which are unsuitable for lichen colonisation. In an effort to find younger control points, we considered two sites reported in Bull and Brandon (1998). This included a flood control wall at Flock Hill (Orwin, 1972) apparently built in AD1940. Our sampling of the lichen on that wall yielded a 98% quantile of 32.62 mm and five largest size of 35.82 mm. Likewise, sampling of the Falling Mountain rockfall deposit formed in AD 1929 (McSaveney and Davies, 2000)

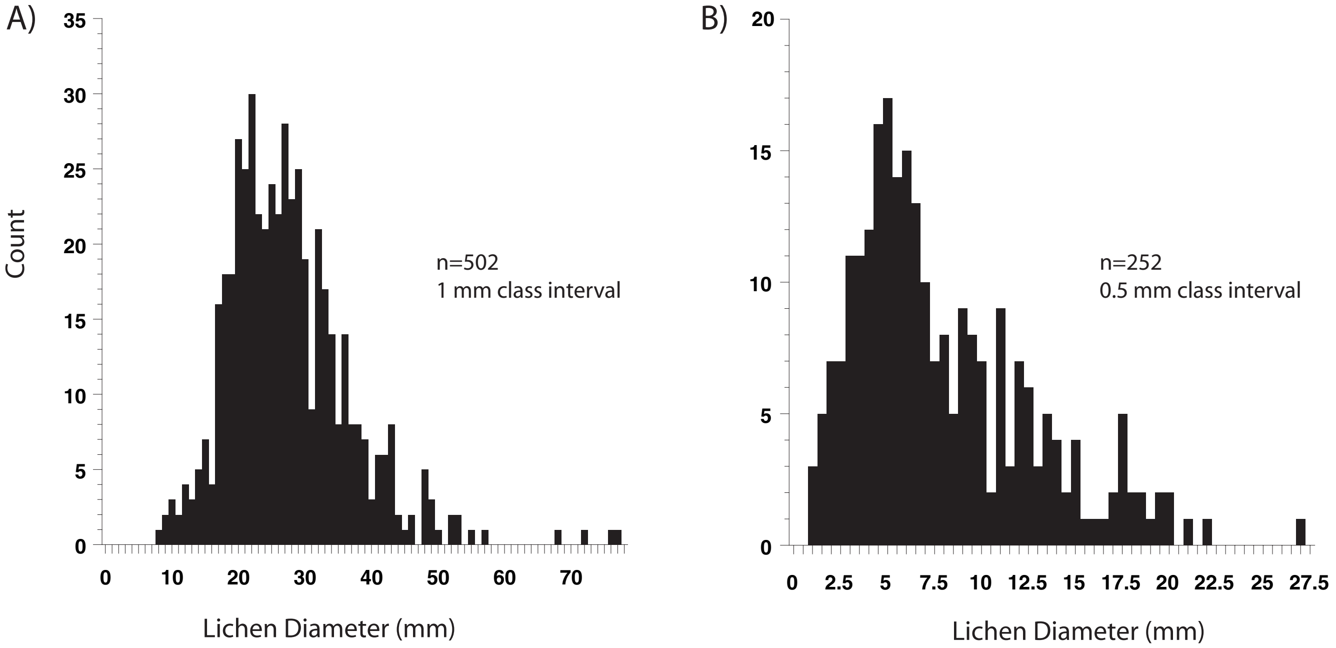

Figure 6 Cumulative histograms of (A) a single moraine, and (B) a single boulder. The data for (A) comes from five separate transects along a single moraine at Mueller Glacier and includes the five counts discussed in the text. This site lies adjacent but just outside the moraine of calibration point M29 (Table 1). The data for (B) comes from a point adjacent and just outside the small moraine containing calibration point C31 (Table 1) on the Classen Glacier foreplane. Note both histograms contain distinct peaks within the overall asymmetrical distribution. In the case of (B) formed on the top of a single boulder these individual peaks must reflect a property of the lichen colonisation, not the age of the boulder. It is an open question whether similar peaks on moraine landforms represent this colonisation processes or landscape stabilisation processes. This problem is avoided by adopting an extreme value representation of the lichen population

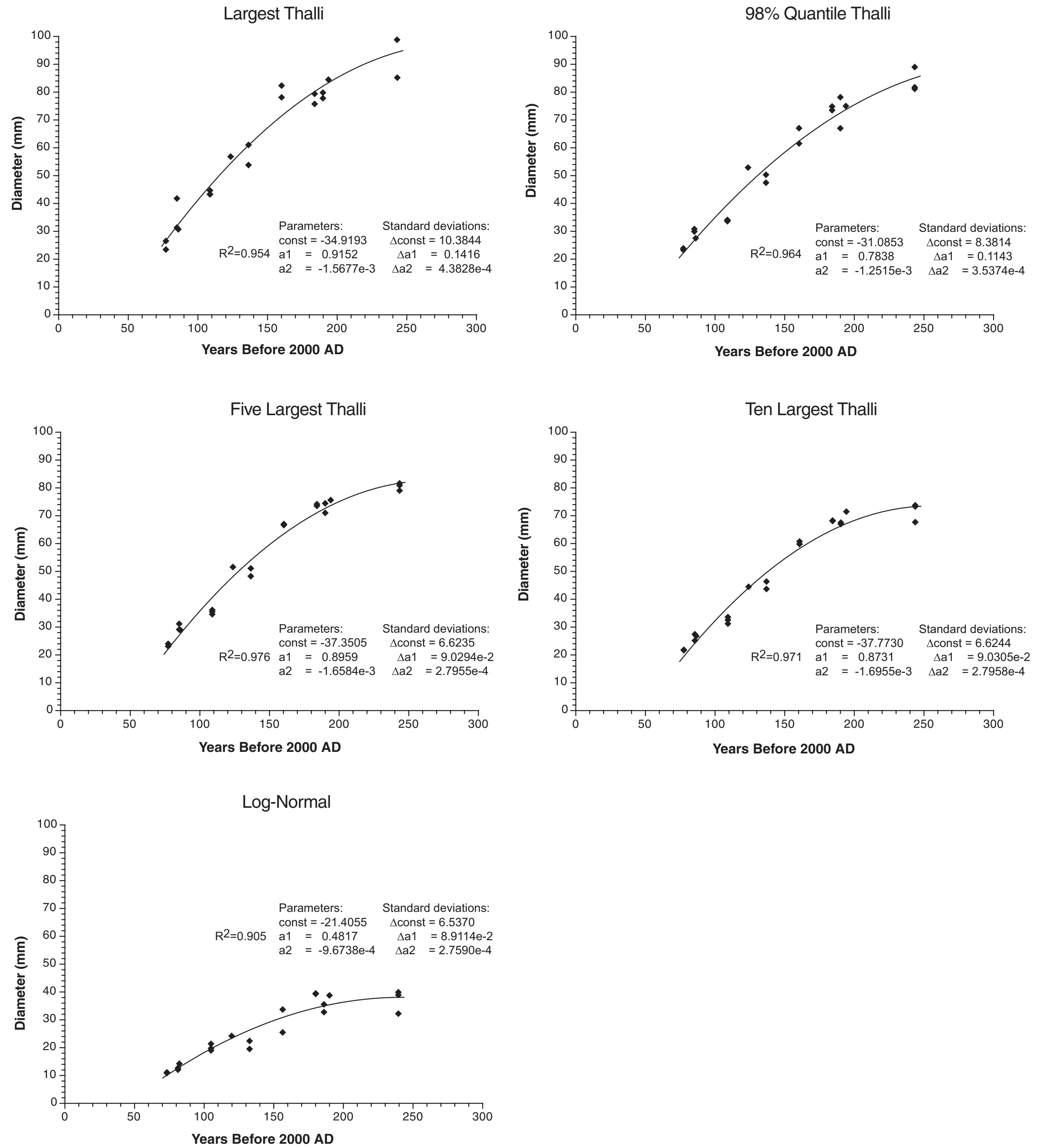

Figure 7 *Rhizocarpon* sp. calibration curves. All calibration data are reduced using various metrics as described in the text. Linear fit for each curve not shown here, but R^2 values are always smaller than for the quadratic fit (Table 3)

Table 3 Equation and regression coefficients

Metric	Linear	Linear R^2	Quadric	Quadric R^2
98% quantile	0.384 × −3.15	0.94	−0.0013 × 2 + 0.784 × −31.08	0.96
10 largest	0.332 × +0.06	0.91	−0.0017 × 2 + 0.873 × −37.77	0.97
5 largest	0.366 × −0.34	0.93	−0.0017 × 2 + 0.896	0.98
Largest	0.415 × +0.06	0.92	−0.0016 × 2 + 0.915 × −34.92	0.95
Geometric means	0.173 × +0.182	0.84	−0.001 × 2 + 0.482 × −21.41	0.91

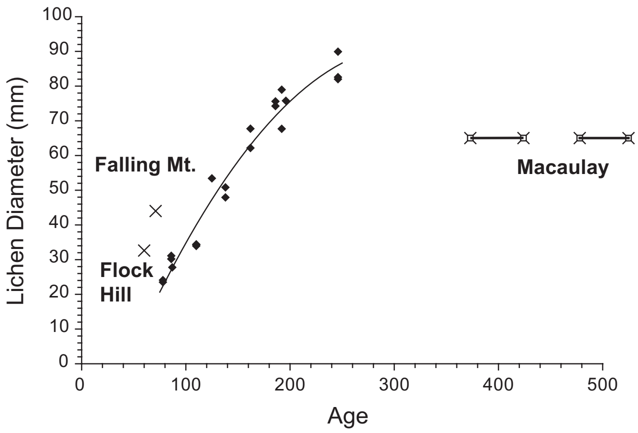

Figure 8 Proposed 98% quantile calibration curve with results from surfaces of known age outside the Mt Cook area (Table 4). The Macaulay site is plotted as the range of calendar ages computed from the radiocarbon sample using Calib 4.3 (Stuiver and Reimer, 1993). Bars represent the intercept of the 1 σ confidence level with the probability curve. The Falling Mt and Flock Hill sites plot younger than our calibration point, perhaps reflecting slower *Rhizocarpon* growth in dryer climate conditions. The lichen diameter for the Macaulay site appears too small for its age and may reflect ecological competition that prevents the lichen from achieving their larger diameter

provided 98% quantile and five largest size of 44.01 and 43.26 mm respectively. In other words, these plot well to the left (younger) than lichen of comparable diameter in the Aoraki/Mount Cook area (Fig. 8). Whereas these sites occur in areas of lower precipitation, these relationships may reflect growth rate dependence on local environmental conditions. Regardless of the reason, counts from these sites are not considered in this curve but rather we rely only on sites in a smaller geographic area, which may limit the extension of this curve to other areas.

On the older end, the quadratic fit of all extreme metrics suggests a slowing of growth with age. To extend this calibration curve, two older catastrophic rockfall surfaces outside of the Aoraki/Mount Cook area were examined. The sites and assigned ages are: Acheron River (500 $\pm$ 69 ^{14}C yr BP NZ 547 (Burrows, 1975) and the Macaulay Valley, 358 $\pm$ 35 ^{14}C yr BP, NZ 4914C (Whitehouse, 1986). Resampling of the organic material trapped beneath rockfall deposits at the Acheron River site provides a new age estimate reported here of 1273 $\pm$ 43 ^{14}C yr BP (Wk-9487). Although the reasons for discrepancy between the two samples at the Acheron River site merit further consideration, both ages have the same relevance for the discussion below. Lichen diameters at both of these sites are smaller than expected by extension of the Aoraki/Mount Cook area curve.

Accepted at face value, the lichen sizes from these radiocarbon-dated sites would imply an inflection in the calibration curve for surfaces older than 300 years. For example at Acheron River, the largest individual lichen observed from 300 measurements is 54.27 mm which would predict an age of about 140 years, an estimate clearly too young. These points are in fact, inconsistent with any reasonable extension of our curve. Field observations on older surfaces show that other plant communities are encroaching upon the *Rhizocarpon*, out-competing the lichen. It may be this ecological overprint that alters the size distribution and prevents lichen development in some areas. Until these apparent issues can be resolved, we refrain from employing *Rhizocarpon* to date surfaces older than 250 years.

Discussion

To assess the general utility of the calibration curve for the Aoraki/Mount Cook area, it is first contrasted with prior studies on the same glaciers and then to efforts elsewhere in New Zealand and then finally to reports from the northern hemisphere. These comparisons must be qualitative, as differences in data collection and presentation techniques exist in the generation of these curves. However, we attempt to minimise this by comparing similar metrics. For example, when another author used a single largest metric, we contrast that with the largest in a sample set of 100; or when another author used a population mean it will be compared with a mean from a sample set of 100 measurements.

At the Mueller Glacier, Birkeland (1981) noted that the Burrows and Orwin (1971) calibration curve was unique because it implied a faster growth rate (53.5 mm per 100 yr) than had been previously reported, and it was linear throughout (e.g. it did not contain an early rapid growth interval). Birkeland (1981) suggested that the older calibration points were incompatible with relative soil data and that perhaps the Burrows and Orwin (1971) results represent only the rapid growth interval. Since Burrows and Orwin (1971) sampled the largest lichen on the moraine, the closest analogue to our data is our largest lichen plot which displays a shallower slope (Fig. 9) which may result from different sample sizes. Innes (1984) suggested that the maximum diameter increases with increased sample area and that the amount of increase depends on the lichen size. For example, at Storbreen, Sweden, increasing the sample area from 16 m^2 to 512 m^2 resulted in a largest lichen diameter increase from18 to 32 mm whereas the same increase in sample area on an older moraine showed a change from 67 mm to 93 mm (Innes, 1984). At Aoraki/Mount Cook, the offset between the Burrows and Orwin (1971) curve and Fig. 8 at 100 years is 23 mm. Thus, the parallel but offset curves here are attributed to sampling influence; but the overall correspondence supports the original growth rates.

Gellatly (1982) built a lichen growth curve based on historical observation for younger control points and based on rock weathering rind (Chinn, 1981) data for older points on the forefields of the Classen, Mueller and Tasman Glaciers. This curve contains some 11 control points, of which seven age assignments are based on the rind data. Geomorphic mapping of the same surfaces demonstrates some inconsistencies with these age assignments. On the Classen Glacier Gellatly (1982) sampled two locations along the large south lateral ridge. Control points C (33.2 mm, diameter reported as the largest inscribed circle) and B (60.4 mm) are taken to be 100 and 340 years old, respectively. However, detailed geologic mapping (Schoenenberger, 2001) shows that control point C is on drift draped upon the crest of an overrun moraine, and thus must be younger than or nearly the same age as control point B located on the same ridge. On the Mueller Glacier, control point G of Gellatly (1982) is assigned an age of 840 years; but this is on a moraine loop assigned a dendrochronology age of AD 1838 (Lawrence and Lawrence, 1965). On the Tasman Glacier control point K (53.4 mm) of Gellatly (1982) lies on the outermost sampled surface and thus is accordingly assigned the oldest age of ca. 1000 yr. However, control points I (64.0 mm) and J (75.9 mm) both have larger lichen but are on geomorphically interior surfaces and hence are assigned younger ages in accordance with accepted geomorphic principles. This creates a major reversal in fig. 4 of Gellatly (1982). As the same situation appears to occur when we employ the older rockfall ages (Fig. 8) it implies that above a critical size, the larger *Rhizocarpon* thalli in New Zealand can populate surfaces of different ages.

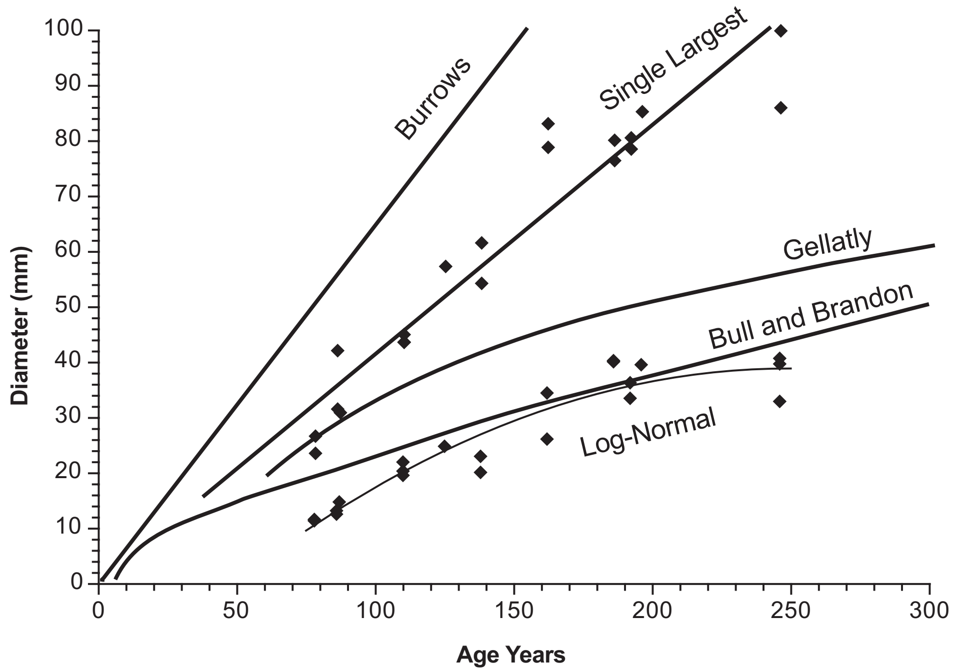

Figure 9 Comparison to prior calibration curves for the Aoraki/Mount Cook area using a metric representing the sampling technique most similar to that of the original author. Our single largest lichen (Table 1) is plotted here with a linear regression to better approximate the methods of Burrows and Orwin (1971). The Gellatly (1982) curve plotted is the log-normal average of the Classen and Tasman Glacier curves. These relationships suggest both Burrows and Orwin (1971) and Gellatly (1982) overestimated the rate of lichen growth in this area, and that the Bull and Brandon (1998) estimate is consistent with the growth curve suggested here

Finally, the overall shape of the Gellatly (1982) curve is unexpected. It is exponential and parallels the Bull and Brandon (1998) curve (Fig. 9)—an unexpected correspondence. Given that Gellatly (1982) reports diameters of individual lichen and Bull and Brandon (1998) report the means for an entire population, these curves should diverge. One possible explanation for the apparent overestimation of ages is that the rind calibration data implies ages too old for moraine surfaces. Because of these various issues, we suggest that the growth curve of Gellatly (1982) may not well represent the lichen growth patterns in the Aoraki/Mount Cook area.

Of the previously proposed regional curves, our effort shows apparent similarities with that of Bull and Brandon (1998). However, detailed examination of the Bull and Brandon (1998) calibration curve raises possible concerns. As in many prior efforts, the lichen growth is divided into the great phase (∼0 to 24 yr in this case) and uniform growth phase (>24 yr) and points that calibrate these separate rates are outlined in tables 3 and 5 respectively of Bull and Brandon (1998). Table 3 lists 14 points with those younger than AD 1956 used to define the great growth period. Of the remainder, we note that four (1929.46, 1881.93, 1855.06, 1848.79) appear to rely on a bootstrapping technique. Regional rockfall events are linked to historical earthquakes of known ages with a peak from the composite data set assigned to one of these events to establish the calibration point. Since Bull and Brandon (1998) report multiple peaks from their regional compilation, it is not clear how a specific peak is assigned to a specific event without a known or assumed calibration curve. Ten of the 11 points in table 5 of Bull and Brandon (1998) rely on the same approach. In other words, the lichen measurements come from a population assembled over a wide geographical area, not from a specific landform with a known age. For example, the Acheron River rockfall (Burrows, 1975) is reported to have a mean peak for the entire population of 84.27 mm (Bull and Brandon, 1998), assuming the original radiocarbon date of Burrows (1975) is correct. Although that age appears to be too young, direct measurements of 300 thalli on the landslide surface at Acheron River found the largest lichen to be only 63.9 mm across (Table 4). In other words, direct measurement on a landform of uniform age failed by a wide margin to produce the predicted lichen size. The assignment of a calibration age based on population distribution depending on an assumed event may need to be reassessed.

A further complication of the Bull and Brandon (1998) curve is that nine of the points in their table 5 rely on radiocarbon dates. Close examination of table 5 shows that in many cases samples for the radiocarbon ages do not come from the same location as the lichen samples raising the possibility of mis-correlation. In addition, radiocarbon ages require conversion to calendar years. A unique solution is often not possible, especially within the last few hundred years (Stuiver and Reimer, 1993). Of the 18 points for the uniform growth period reported in Bull and Brandon (1998), only three do not suffer one or more of the problems noted above. Thus for our purposes of dating landforms in the Akaroka/Mount Cook area the methodology of Bull and Brandon (1998) is not employed.

Porter (1981) compared *Rhizocarpon* growth curves from various regions and concluded that slow growth rates occur in areas of low annual precipitation and low mean temperatures and conversely faster growth rates occur where high precipitation values and milder temperatures occur. The New Zealand data are consistent with this general observation (Fig. 10). Simple comparison shows that most prior reports have nearly similar slopes, but that the growth rate changes. The data reported here fall well in the middle of the reported data from the Cascade Range (Porter, 1981; O'Neal and Shoenenberger, 2003) summary, and above the rates reported in Alaska or Lapland (Denton and Karlen, 1973) (Fig. 9). We argue the newly derived data have overall consistent patterns with growth patterns reported elsewhere.

Table 4 Other sample sets

Sample	Count	Largest	98% quantile	5 largest	10 largest	Log-normal
Acheron, all	300	63.94	54.27	59.80	56.31	28.79
Acheron 1	100	59.17	56.62	56.03	51.20	27.59
Acheron 2	100	53.17	45.33	45.15	42.21	26.93
Acheron 3	100	63.94	57.29	56.06	49.44	30.06
Falling Mt, all	89	68.79	44.01	43.26	36.46	11.43
Falling Mt 1	31	28.45	28.45	25.48	23.23	11.79
Falling Mt 2	36	44.01	44.01	34.61	29.13	9.69
Falling Mt 3	22	68.79	68.79	37.46	28.78	12.71
Macaulay, all	300	74.09	65.03	69.46	66.80	34.88
Macaulay, 1	100	59.53	55.32	54.16	49.51	25.91
Macaulay 2	100	69.38	66.42	66.26	62.83	38.64
Macaulay 3	100	74.09	68.14	66.00	61.99	37.68
Flock Hill, all	435	39.67	32.62	35.82	34.10	13.84
Flock Hill top	109	28.65	21.84	23.41	21.49	9.56
Flock Hill north	158	32.93	25.93	28.89	26.49	13.42
Flock Hill south	168	39.67	34.22	35.82	33.85	17.57

The data reduction approaches employed here may have wider applications. The high regression coefficients of the quadratic equation describing our data may indicate that such a form better represents the growth history of lichen than does the rapid-growth/slow-growth form often suggested. The exponential form of the growth curve may have a basis in controlled growth rate measurements. Armstrong (1983) reported individual thalli smaller than 20 mm showed a complex growth pattern, individuals from 20 to 45 mm in diameter had a constant growth rate and lichens larger than 45 mm showed a marked decline in growth. This implies that the shape of the lichen growth curve is not the simple rapid growth followed by linear growth as generally assumed. Karlen and Black (2002) revisited and remeasured sites in northern Sweden 30 years apart and found that for those younger than 100 years growth rates were typically faster than 0.35 mm yr^{-1}, whereas older individuals displayed slower growth. For the 33 sites considered, those data display a negative natural log decay.

The analysis of the data set here shows that for all possible metrics a simple linear regression of the data has a lower correlation coefficient than a quadric fit. There appears to be no natural break in the data plots as required for fitting two linear segments. Since we are primarily concerned with dating surfaces of similar geomorphic ages, we retain the quadric form as it avoids the problem of deciding exactly where such a transition takes place and thus potentially applying the wrong curve. If natural lichen communities obey similar growth patterns as Armstrong (1983) observed, a simple exponential curve may be a better representation than two straight lines.

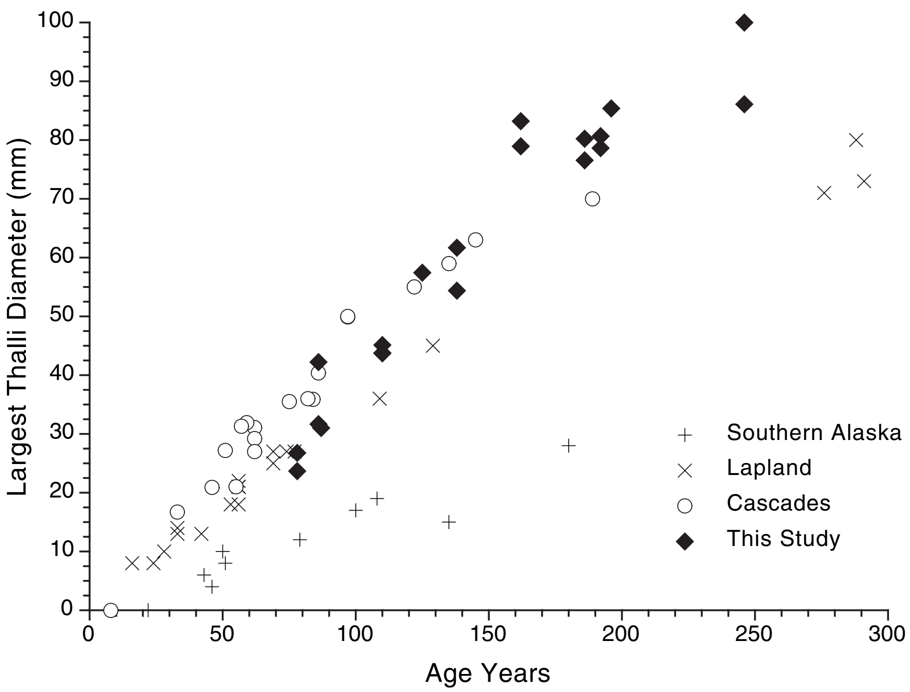

Figure 10 Comparison of largest lichen vs. age from the Aoraki/Mount Cook area with those derived from Southern Alaska and Lapland (Denton and Karlen, 1973) and the Cascades (O'Neal and Shoenenberger, 2003). Note that in the original work, Denton and Karlen (1973) considered the control points as limiting values. Several possible fitted curves would provide a growth curve for the younger ages, but these trends diverge with older ages and a quadratic solution may be suitable

Conclusions

This work provides a refined calibration curve for *Rhizocarpon* from the Aoraki/Mount Cook region of New Zealand. Landform development whereby glaciers retreated into lakes prevented the adequate characterisation of young surfaces and competition with other plant species adversely impacts lichen populations older than 250 years. Further, it appears that over this interval a quadratic curve provides the best fit, thus avoiding the slow–rapid growth issue. By taking calibration points directly on the geomorphic surfaces that we intend to study, this analysis indicates that a simple metric can be derived.

Bull and Brandon (1998) made a strong appeal to approach lichen age dating efforts with more statistical rigour. To this end we amassed a large data set to assess several different metrics representing the age of freshly deglaciated landforms. Employing simply the single largest lichen raises concerns whether the largest lichen has been identified and whether there is a dependence of lichen size on sample size. Any average of a population flattens out with increasing age, reducing the ability to separate out unknown samples with similar size lichen.

Thus, the 98th percentile, which is independent of sample size, fit to a quadric, strikes a balance and may have more widespread utility. This suggests that the work necessary for a population-based approach should be considered on a case-by-case basis.

Acknowledgements We thank the Department of Conservation, New Zealand, especially Ray Bellringer of Aoraki/Mount Cook National Park, for permission and assistance to undertake these studies, and NOAA Abrupt Climate Change Program for support. James Shulmesiter, William Bull and Donald Rodbell all raised probing questions and offered key suggestions to improve our presentation of this work.

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The 'Little Ice Age' maximum in the Southern Alps, New Zealand: preliminary results at Mueller Glacier

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Abstract: Lichenometric-dating studies using the yellow-green *Rhizocarpon subgenus* at Mueller Glacier in the region of Mt Cook, Southern Alps, New Zealand, reveal a 'Little Ice Age' maximum about AD 1725/1730. Differences from previous studies are shown to result from different methods, especially the type of mathematical functions used for calculating the lichenometric dating curves. Previous work also used variable sample sizes, distal moraine slopes, and, to some extent, different fixed points. Schmidt hammer measurements enable the differentiation of 'Little Ice Age' from pre-'Little Ice Age' frontal moraines in the outer glacier foreland and confirm the status of the 'Little Ice Age' as a separate glacier advance among several advances during the Holocene.

Key words: 'Little Ice Age', relative-age dating, lichenometry, Schmidt hammer, glacier variations, Holocene, New Zealand.

Introduction

The 'Little Ice Age' has been recognized as an episode of late-Neoglacial glacier advance in many mountain areas (Grove, 1988). However, research has mainly concentrated upon mountain areas of the Northern Hemisphere, e.g., the European Alps (Zumbühl *et al*., 1983), Scandinavia (Bickerton and Matthews, 1993) and North America (Luckman, 1993). As a comparison of the timing of the 'Little Ice Age' maximum and detailed chronologies of glacier front variations between Scandinavia and the European Alps has revealed important differences (Winkler, 1996), the postulated synchronous 'Little Ice Age' and Holocene glacier chronology (e.g., Röthlisberger, 1986) becomes questionable. Despite regional (and temporal) variations, 'global' trends in glacier variations are often used in connection with simulations and the discussion of 'global change' (Oerlemans, 1994).

Alongside the glaciological data available for recent decades (e.g., IAHS/UNESCO, 1993; 1998), detailed and accurate chronologies of the 'Little Ice Age' are necessary for development and testing such simulations. A major goal of the present study was therefore to test whether the chronology of the 'Little Ice Age' in the Southern Hemisphere is similar to that of the Northern Hemisphere. In the case of the Southern Alps of New Zealand, this question cannot be answered based on previous work due to major disagreement in the dating of Holocene moraine sequences (see below). Furthermore, as mountain glaciers in the Northern Hemisphere have exhibited different glacial dynamics during recent years (IAHS/UNESCO, 1993; 1998; Winkler *et al*., 1997) and have experienced their 'Little Ice Age' maxima at quite different dates (Grove, 1988; Winkler, 1996), it would be interesting to search for possible correlations between the glaciers of the Southern Alps and glaciated regions of the Northern Hemisphere.

Local setting

Mueller Glacier is a 13.9 km long valley glacier with an area of 22.5 km^2 (Chinn, 1996). It is located east of the main divide close to Mt Cook (Figure 1). The glacier foreland (Figure 1) is dominated by massive lateral moraines with crests up to 120 m above the glacier surface. Apart from these 'alpine type' lateral moraines (Winkler and Hagedorn, 1999), several smaller latero-frontal/frontal moraine ridges occur in the outer foreland. About 37% of the glacier surface is covered by supraglacial debris (Chinn, 1996). The almost entirely debris-covered lower tongue obscures the accurate identification of the present glacier snout. In addition, a proglacial lake has formed in contact with the glacier.

Previous work

There have been several attempts to date the moraines at Mueller Glacier. Radiocarbon dating has been carried out on organic material found within lateral moraines at Mueller Glacier and neighbouring glaciers (e.g., Gellatly *et al*., 1988; cf. critical remarks from Kirkbride and Brazier, 1998). Lawrence and

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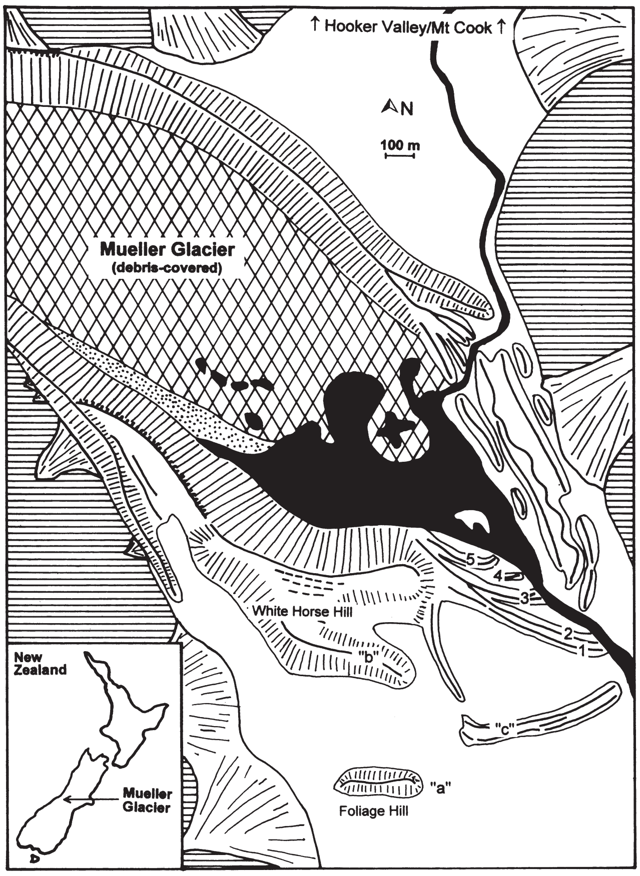

Figure 1 The glacier foreland of Mueller Glacier. The dated moraines in the southeastern foreland are indicated.

Lawrence (1965) used dendrochronology. Later lichenometric-dating studies were made by Burrows and Lucas (1967), Burrows and Orwin (1971) and Burrows (1973). Gellatly (1982; 1984; 1985) presented a revised moraine chronology using historical evidence, lichenometry and weathering rind data. The aim of this study was to judge which of the different chronologies is correct, based on lichenometry and supported by Schmidt hammer measurements.

Lichenometry

It was necessary to establish a new lichenometric dating curve for Mueller Glacier because previous studies used non-standard methods of uncertain validity (cf. Innes, 1985a; Matthews, 1994). Burrows and Orwin (1971) presented a linear function to express lichen growth. In combination with the use of Lawrence and Lawrence's (1965) dendrochronological dates as fixed points (providing minimum ages with an unknown time gap between moraine formation and tree colonization), their dating curve overestimates the growth rate of lichens and underestimates the age of the moraines. Gellatly (1982) used weathering rind data based on Chinn's (1981) method to establish fixed points at older moraines. Apart from the lack of accuracy that disqualifies the use of weathering rind-datings as fixed points (see McCarroll, 1991, for criticism on the accuracy of Chinn's (1981) method and especially its application by Gellatly (1984) for the dating of Holocene moraines at Mueller Glacier), Gellatly (1982) does not use a semi-logarithmic dating curve either. As a consequence, moraines are dated much older compared with Burrows (1973). Both studies did not use sample sites of similar areal extent (cf. Innes, 1984a) and measurements were mainly restricted to distal slopes and crests of moraines. Burrows (1973) measured the largest diameter of the single largest lichen, whereas Gellatly (1982) uses the diameter of the largest circle inscribed within the lichen thallus (short axis).

Lichenometric measurements of the present author were restricted to the yellow-green *Rhizocarpon subgenus* (Innes, 1985b; Poelt, 1988) without differentiating between *R. alpicola* and *R. geographicum*. Sample sites were taken as 25 m long segments and only proximal sides or crests of moraines were sampled. Measurements on numerous segments of moraine ridges in all parts of the glacier foreland should include the areas of optimal ecological conditions ('green zones') for lichen growth. Among the factors influencing lichen growth in the Southern Alps, unstable (especially proximal) moraine slopes, thick and abundant supraglacial debris cover and strong competition with other lichens, mosses and vascular plants have to be considered. However, the southeastern part of the glacier foreland provides relatively good conditions for lichenometry. Taking the less than optimal conditions for the application of lichenometry into account, the mean of the largest diameter of the five largest lichens of the site with the largest mean value was used to calculate the lichenometric dating curves.

Historical evidence from Mueller Glacier (cf. Gellatly, 1985) allows the establishment of three fixed points for the calculation of the dating curve as a semi-logarithmic function (cf. Matthews, 1994). Although some controversy over its interpretation exists (cf. Burrows and Orwin, 1971; Gellatly, 1982), the ice front position of 1860 can be related to the *M-MUE* 3 moraine according to historical observations and a sketch map presented by Gellatly (1985). Burrows and Orwin (1971) date the innermost moraine loop (*M-MUE* 5) to 1930, but there is no historical evidence of an advance at this time (Gellatly, 1985). As a slight advance of Mueller Glacier with a thick debris cover was documented in 1905 (Gellatly, 1985), it seems likely that the *M-MUE* 5 was built during that advance (Gellatly, 1982, used 1890 as the date for *M-MUE* 5). Interpreting historical reports and the sketch map given by Gellatly (1985), either 1890 or 1895 could be taken as dates for the short *M-MUE* 4 moraine (not clearly mapped by Burrows, 1973, or Gellatly, 1982; 1984). Statistical regression analysis reveals better correlations for the '1895'-alternative. A family of four lichenometric dating curves (Table 1; Figure 2) was calculated using both alternatives for *M-MUE* 4. A test using the fixed points of Gellatly (1982; 1985), i.e., 1890 for *M-MUE* 5 and 1860 for *M-MUE* 3 for the construction of a semilogarithmic dating curve ($\log y = 0.0047\times + 1.8823$ $r^2 = 1$) gave an unexpected young age (AD 1786) for the outermost 'Little Ice Age' moraine and an abnormally long time gap between moraine formation and first colonization by lichens (> 75 years). This supports, in the opinion

Table 1 Lichenometric dating results of Mueller Glacier

Moraine	Mean five largest lichens (mm)	SL 1	SL 2	SL 1w	SL 2w
M-MUE 1	94.8	AD 1726	1732	1723	1721
M-MUE 2	92.4	AD 1737	1742	1735	1732
M-MUE 3	55.8	AD 1860	1859	1860	1857
M-MUE 4	38.8	AD 1895	1893	1896	1893
M-MUE 5	33.2	AD 1905	1903	1905	1903

SL 1: $\log y = 0.0075x + 1.7252$.
SL 2: $\log y = 0.0072x + 1.7439$.
SL 1w: $\log y = 0.0076x + 1.7199$.
SL 2w: $\log y = 0.0075x + 1.7331$.
Basis of the lichenometric dating curves: SL 1 was calculated using a '1895' date for *M-MUE* 4; SL 2 using a '1890' date (see text); SL 1w and SL 2w using an additional 'theoretical' fixed point derived from adjustments to dating curves given by Winkler and Shakesby (1995) from the Ötztal Alps/Austria (see text).

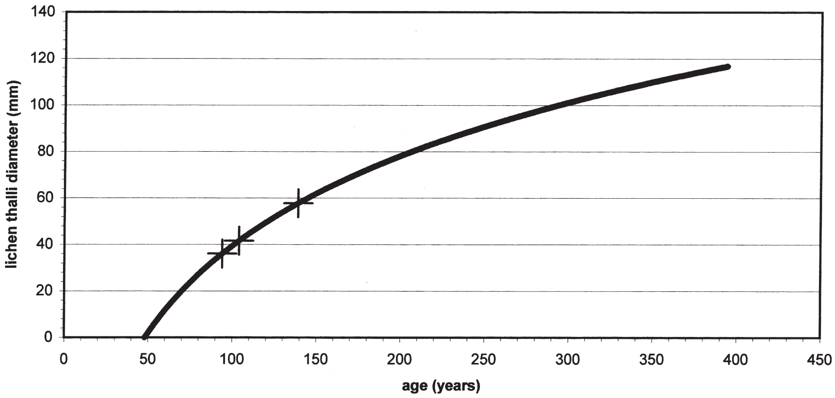

Figure 2 The SL 1 lichenometric dating curve (fixed points marked).

of the present author, the preferred interpretation of the historical evidence presented above.

As the growth rates for the lichens at Mueller Glacier and the three given fixed points fit extremly well with existing lichenometric dating curves from the Ötztal Alps, Austria (Winkler and Shakesby, 1995) and ecological conditions for lichens are therefore considered similar, an attempt was made to improve the lichenometric dating curves by the construction of a ‘theoretical’ fixed point (of older age) derived from the adjustment of the Mueller Glacier curves to Ötztal curves. However, in the final dating only curves based on the three original fixed points from Mueller Glacier were used.

Schmidt hammer measurements

Owing to its accuracy as a relative-age dating technique, the Schmidt hammer cannot be used to distinguish between moraines formed within the ‘Little Ice Age’ (McCarroll, 1991). However, this technique enables the separation of ‘Little Ice Age’ moraines from older Holocene moraines (e.g., Matthews and Shakesby, 1984) and gives clear indication whether older Holocene surfaces (rockfall-avalanches, but also moraines) were built in the same period (Nesje *et al*., 1994).

Moraine complex *M-MUE* ‘c’ outside the ‘Little Ice Age’ moraines dated by lichenometry should comprise at least two advances between 1490 and 2940 a BP following Gellatly (1984). To examine this dating, intense Schmidt hammer measurements were carried out by the present author. At each test site, 50 boulders were tested by one blow per boulder and measurements were restricted to massive sandstones of the Torlesse group (Spörli and Lillie, 1974; MacKinnon, 1983). Special effort was made to avoid boulders that showed even slight movement during testing and test sites were kept as small as possible. The results of numerous test sites on this moraine complex show no statistically significant differences between Schmidt hammer rebound values (r-values) from different moraine segments. All means of r-values for *M-MUE* ‘c’ lie within the 95% confidence interval of the other sites (Figure 3), i.e., within the range of accuracy that can be expected from this method (cf. Winkler and Shakesby, 1995). Therefore, the whole moraine complex *M-MUE* ‘c’ must be seen as formed during one period of glacier advance. Additionally, Schmidt hammer measurements show that Foliage Hill (*M-MUE* ‘a’) is clearly older than *M-MUE* ‘c’, as is the oldest part of White Horse Hill (*M-MUE* ‘b’). Whether *M-MUE* ‘a’ and ‘b’ were built up during the mid-Holocene or are older cannot be judged. Compared to Schmidt hammer measurements in Norway (Matthews and Shakesby, 1984; Nesje *et al*., 1994; Winkler, unpublished data), the difference between mean r-values from *M-MUE* ‘c’ and Foliage Hill (Figure 3) would be comparatively low for the age difference of 7000 a BP given by Gellatly (1984). Until further measurements on dated early-Holocene surfaces are available, moraine formation between *c*. 5000 and 3000 a BP seems to be likely in the light of differences in r-values.

Discussion and conclusion

The results derived from the application of lichenometric dating curves indicate a ‘Little Ice Age’ maximum at Mueller Glacier about AD 1725/1730 (1721–1732; Table 1). This advance was followed by subsequent advances or stillstands around 1740, 1860, 1895 and 1905. A major advance around 1750 has been suggested for some glaciers west of the divide, such as Franz Josef and Fow Glacier (Lawrence and Lawrence, 1965; Coates and Chinn, 1992), but these datings may not be reliable (methodological problems of several relative-age dating techniques in the heavily vegetated outer glacier forelands). Application of the dating curves from Mueller Glacier at Tasman Glacier, the main ‘Little Ice Age’ advance occurred later (nineteenth century: Winkler, unpublished data). This could be related to different local climate, different moraine morphology or, excluding all possible methodological influences, a longer response time of Tasman Glacier with a longer duration of the maximum.

The results for the dating of the ‘Little Ice age’ moraines at Mueller Glacier, especially for the ‘Little Ice Age’ maximum, are new and stand in contrast to earlier studies. Differences from previous research can be explained by the more carefully controlled application of lichenometry, especially in the calculation of lichenometric dating curves. Although the results, seen in a broader context, are restricted to a single glacier foreland and therefore preliminary, they are important in the context of glacial dynamics in the Southern Alps. The glaciers west of the watershed are experiencing a strong advance (Franz Josef Glacier: 1000 m advance in the last 15 years), while the eastern glaciers had several years with positive net balances and show a thickening in the accumulation areas (T. Chinn, personal communication). This glacier behaviour may be attributed to an increasing magnitude and frequency of El Niño events during recent decades (Fitzharris *et al*., 1997).

As a similar strong advance is present in the Northern Hemisphere (maritime Scandinavia: Winkler *et al*., 1997) and the ‘Little Ice Age’ maximum during the eighteenth century was similar in southern Norway (Erikstad and Sollid, 1986; Bickerton and Matthews, 1993; Winkler, 1996) and (apparently) northern Norway (Innes, 1984b; Winkler, unpublished data), this suggests the possibility of a common trend in maritime mountain areas in both hemispheres. However, the pre-‘Little Ice Age’ moraines at Mueller Glacier and evidence of multiple Holocene glacier advances in Mt Cook National Park (Gelletly *et al*., 1988) indicate

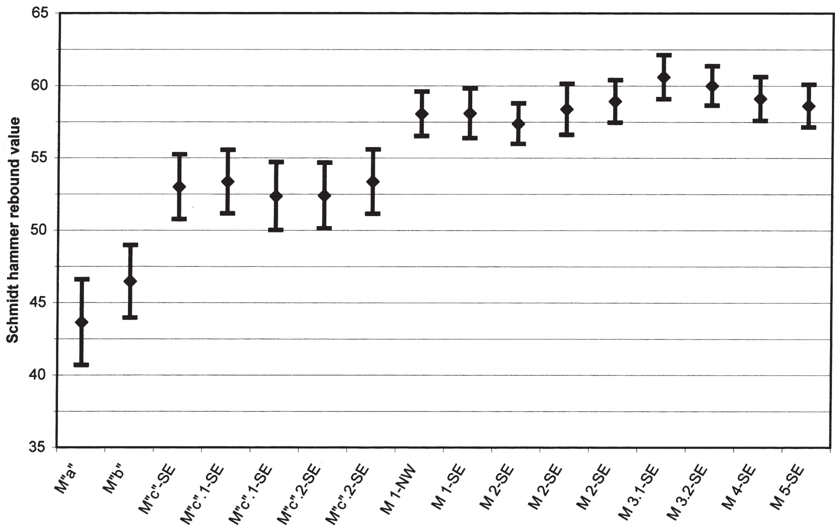

Figure 3 Results of the Schmidt hammer measurements on different segments of moraines in the glacier foreland of Mueller Glacier. Results are means with the 95% confidence interval. Note the difference between the 'Little Ice Age' moraines (*M-MUE* 1–5) and *M-MUE* 'a'–'c' formed during older Holocene advances. There are no statistically significant differences between measurements on the moraine complex *M-MUE* 'c'.

similarities to the European Alps (Röthlisberger, 1986). More research is now needed to test the results at Mueller Glacier and detect any regional trend.

Only detailed regional studies considering differences in climate and glaciology, especially between maritime and continental mountain areas, can improve the record of the 'Little Ice Age'. As a 'global' glacier behaviour does not exist today, the 'Little Ice Age' is far from being a parallel and uniform period of glacier advance in mountain areas of both hemispheres. Improving its chronology therefore holds considerable potential for a better understanding of the complex relationship between glaciers and climate.

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GEOLOGIC TIME SCALE

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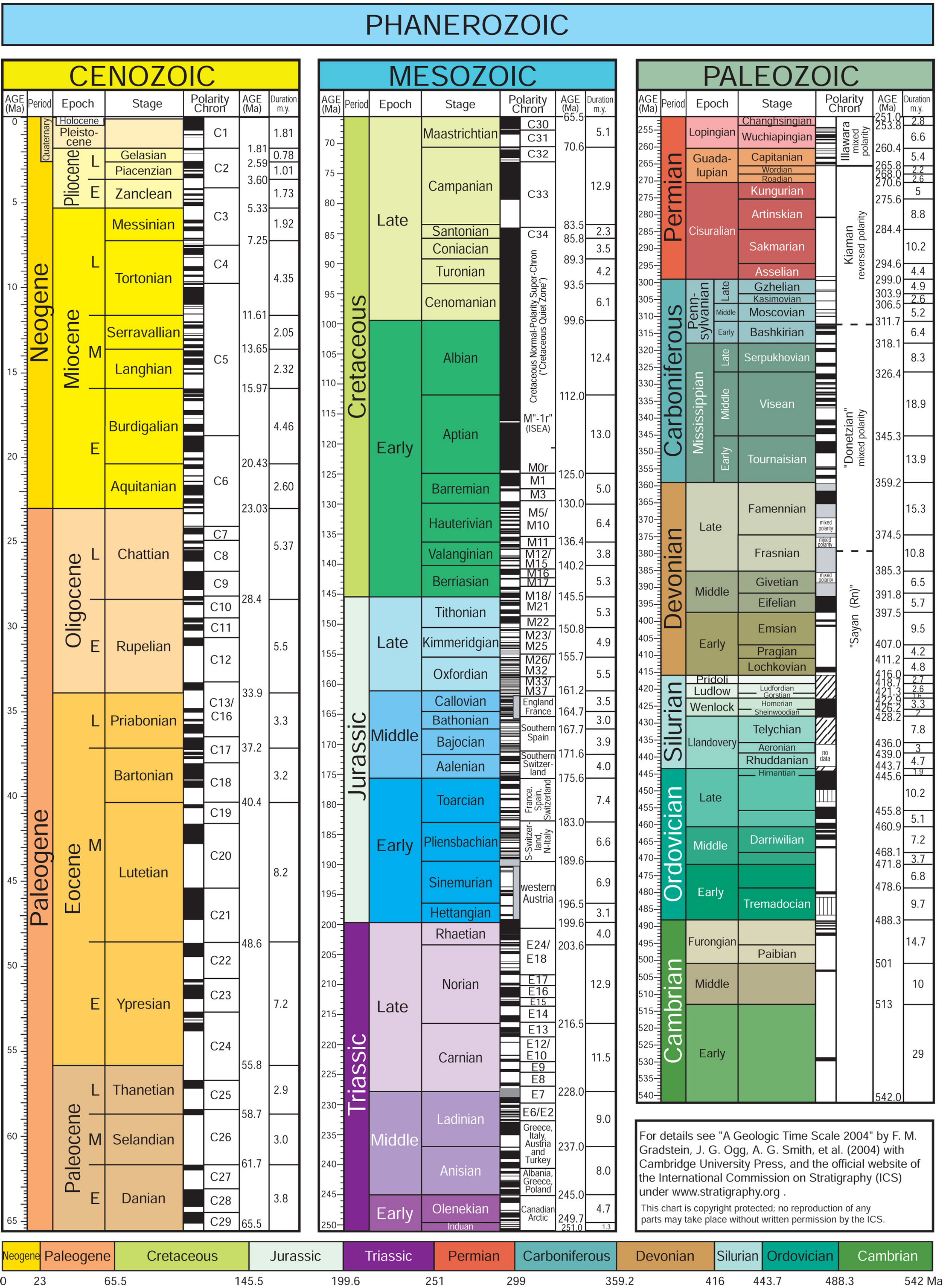

For details see "A Geologic Time Scale 2004" by F. M. Gradstein, J. G. Ogg, A. G. Smith, et al. (2004) with Cambridge University Press, and the official website of the International Commission on Stratigraphy (ICS) under www.stratigraphy.org .